# Top Quark Production at the Tevatron

Erich W. Varnes
*University of Arizona*

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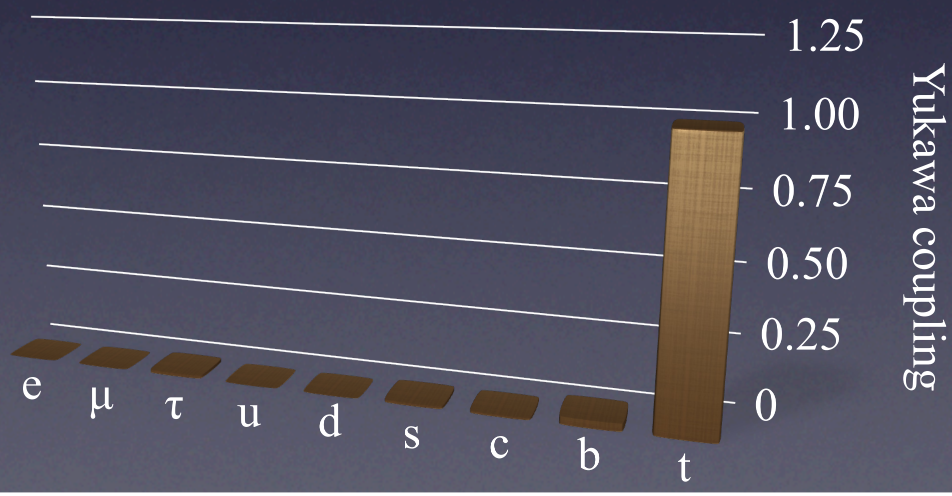
# The Top Quark in the SM and Beyond

- All top quark properties (except its mass) are fixed in the SM
  - It's "just" another isospin +½ quark
- In addition, the SM predicts $|V_{tb}| \approx 1$
  - So the top has one dominant decay mode: $t \to Wb$
- Most of the interest in top quark physics comes from the potential to find non-standard effects
- Is Yukawa coupling a hint?




Top is the only fermion with a "natural" coupling

# What We Can Learn From Top Production

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Are there more than three fermion generations?

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Single top quark production

Top quark pair cross section

Search for boosted top quarks

$M_{tt}$ distribution

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- Measurements in this talk
  - Single top quark production
  - Top quark pair cross section
  - Search for boosted top quarks
  - $M_{tt}$ distribution

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In addition, well-understood production measurements provide the basis for measuring other top quark properties (see T. Schwarz's talk) and for other searches

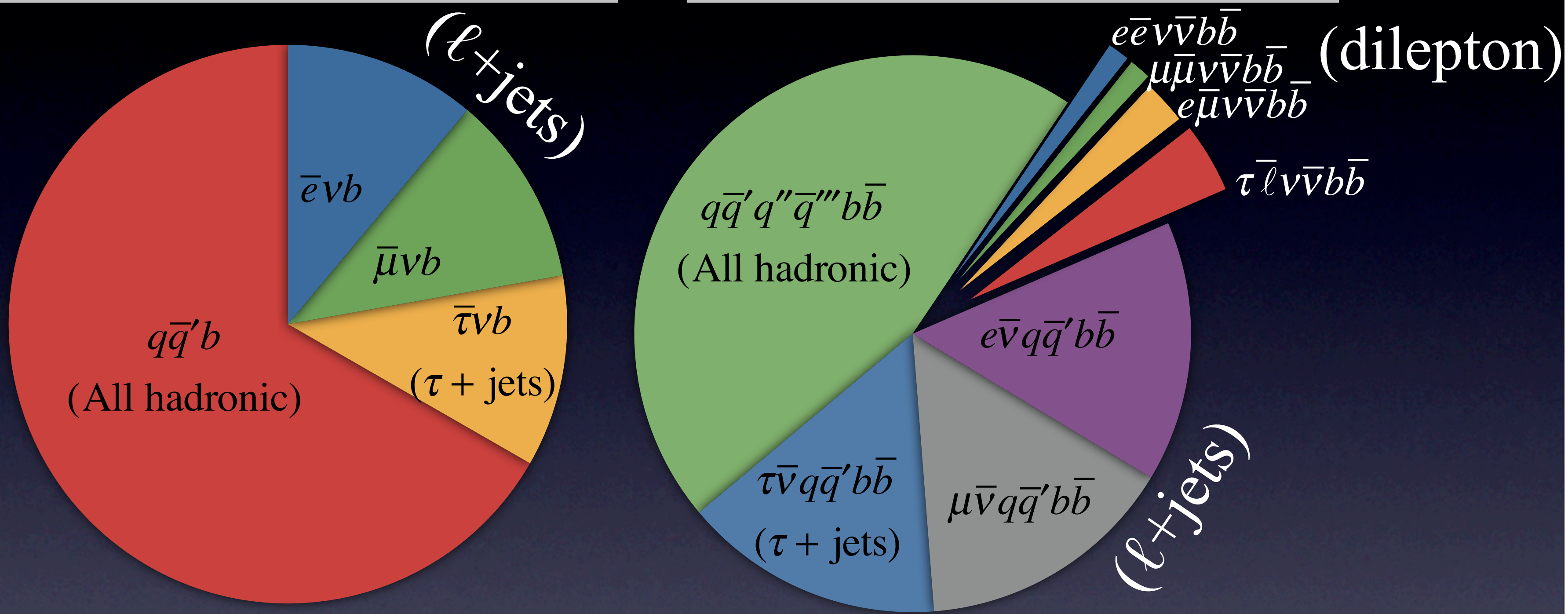
# Top Quark Signatures

- Single top quark:

Tevatron cross section: ~3 pb

- $t\bar{t}$ pair:

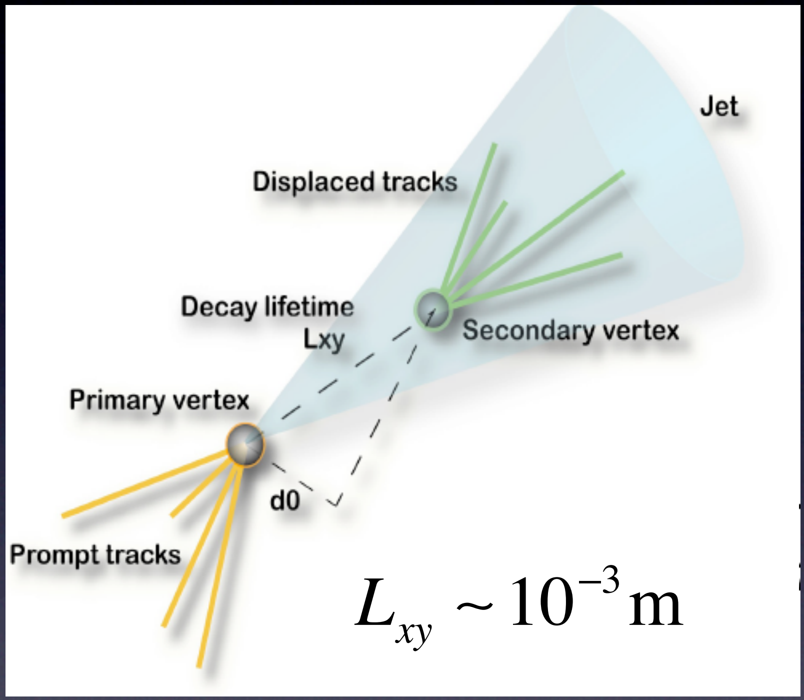
Tevatron cross section: ~7 pb



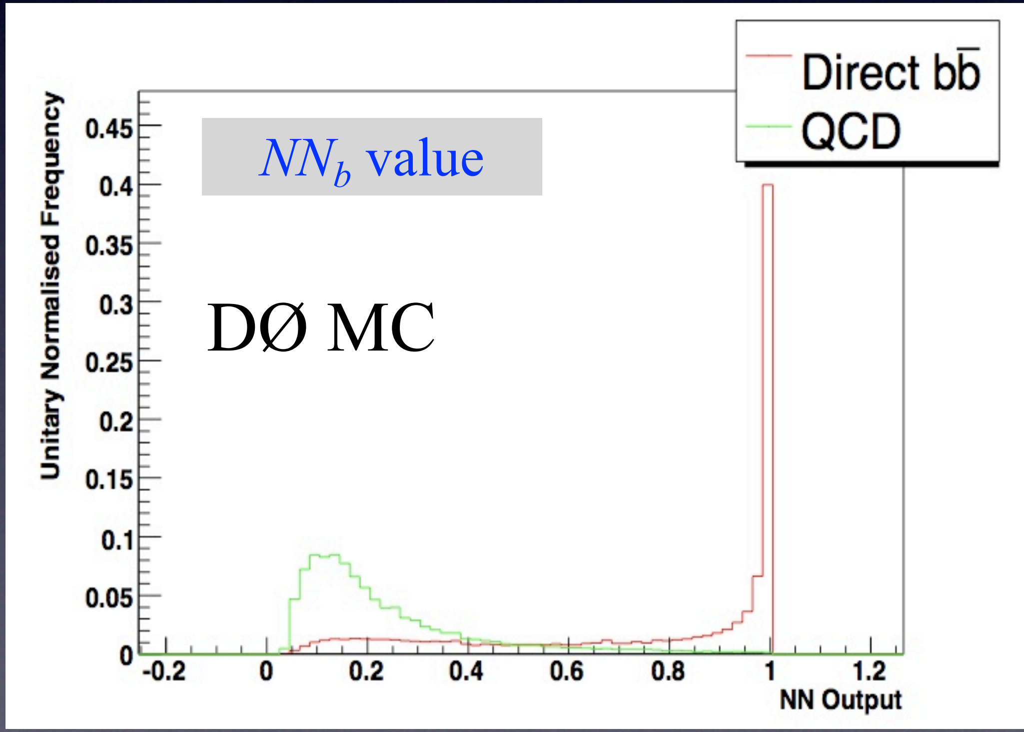

- Dominant backgrounds arise from vector boson + jet production
  - Good $b$ jet and lepton identification, missing $E_T$ resolution help in finding top quarks

# Identification of $b$ jets

- Based upon relatively long lifetime of $b$ quark



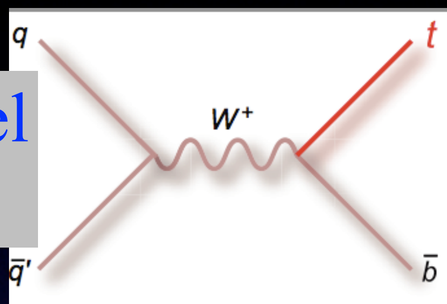

Combine several track and secondary vertex quantities in multivariate discriminant



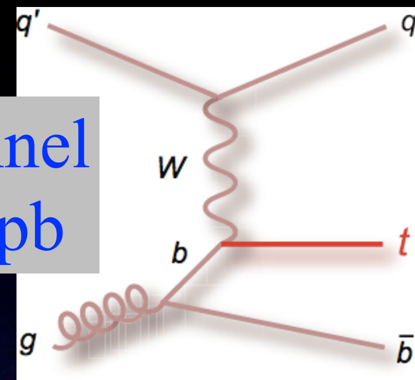
# Top Quarks, One at a Time

- Main production diagrams at the Tevatron:

s-channel
0.88 pb




t-channel
1.98 pb




- Direct access to the *tWb* coupling
  - overall rate and ratio between s- and t-channels are sensitive to new physics, as are angular distributions
- Experimental challenge:
  - cross section ~half of $t\bar{t}$
  - large backgrounds from $W + 2$ jets

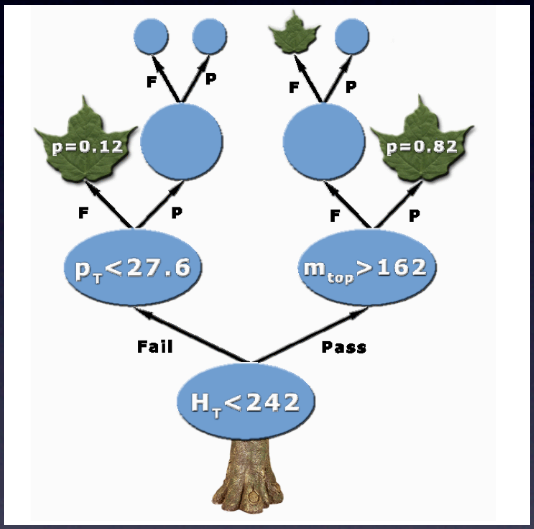
S/B ~1/200 before *b*-tagging

- Need multivariate techniques to extract signal

# Multivariate Methods

Goal: Given a set of measurements **x**, find $p(S|\mathbf{x}) = \dfrac{p(S)\,p(\mathbf{x}|S)}{p(S)\,p(\mathbf{x}|S) + p(B)\,p(\mathbf{x}|B)}$

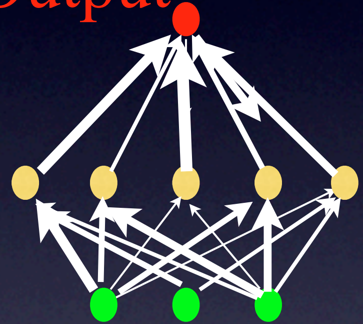
## Boosted decision tree




Training determines shape of tree

Iterative "boosting" improves performance

## Neural network




Train on MC samples to optimize weights

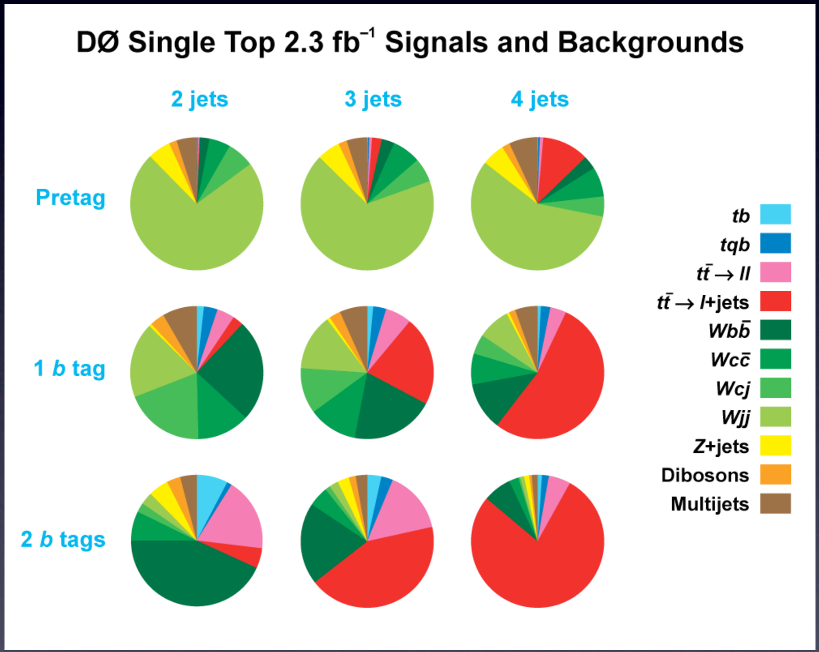
## Matrix element

- Calculate $p(S|\mathbf{x})$ from signal and bkg differential cross section matrix elements
- Integrate over detector resolution

# Searching in Sub-channels

- ℓ+jets channels most promising
- Depending on production diagram, gluon radiation, and detector efficiency, single top production can create several signatures
  - e.g. 2, 3 or more jets, with 0, 1 or 2 identified as *b* jets
- Each such signature has its own characteristics and signal-to-background ratio

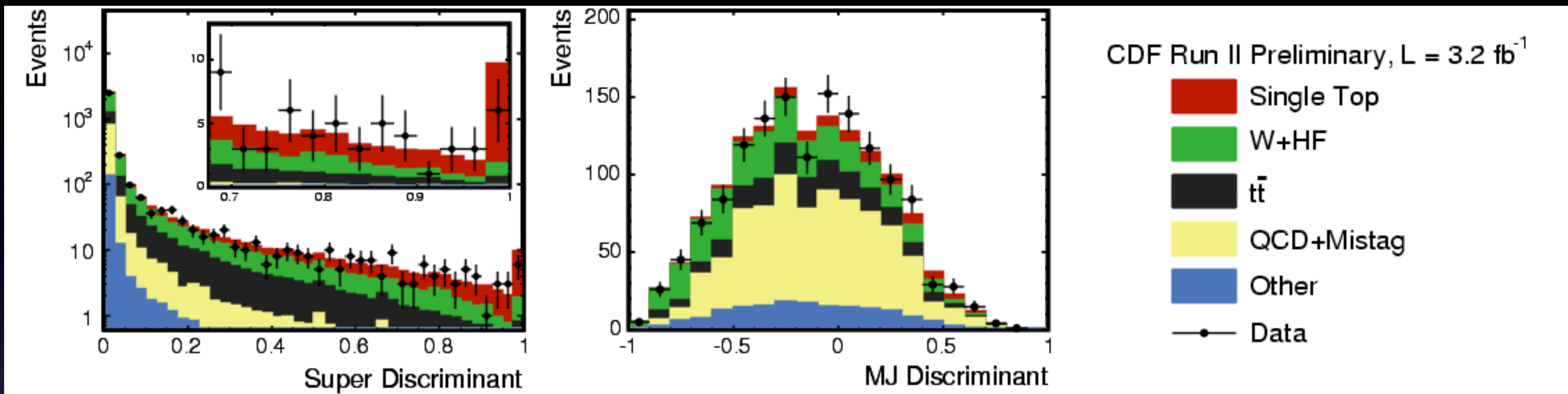
- Both CDF and DØ treat these signatures as distinct "sub-channels" with their own optimized multivariate selections



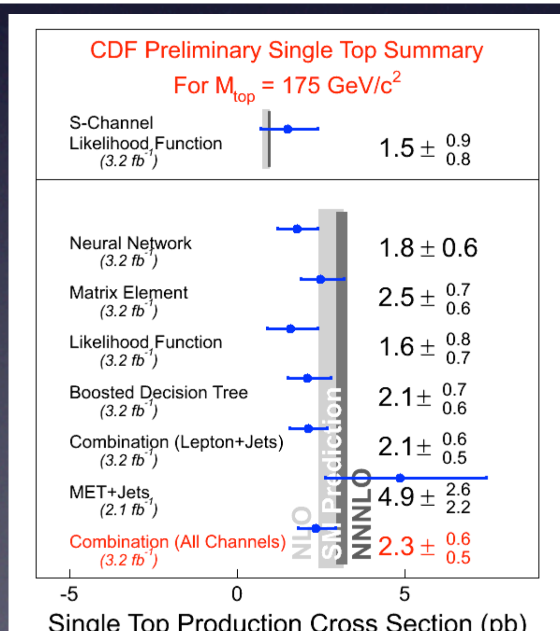

The summary plots on the next slides reflect a large analysis effort

# Single Top At CDF

- $\ell$+jets: Outputs from BDT, ME, and NN are input to final NN




- Result is combined with missing $E_T$ + jets




$m_t = 175$ GeV

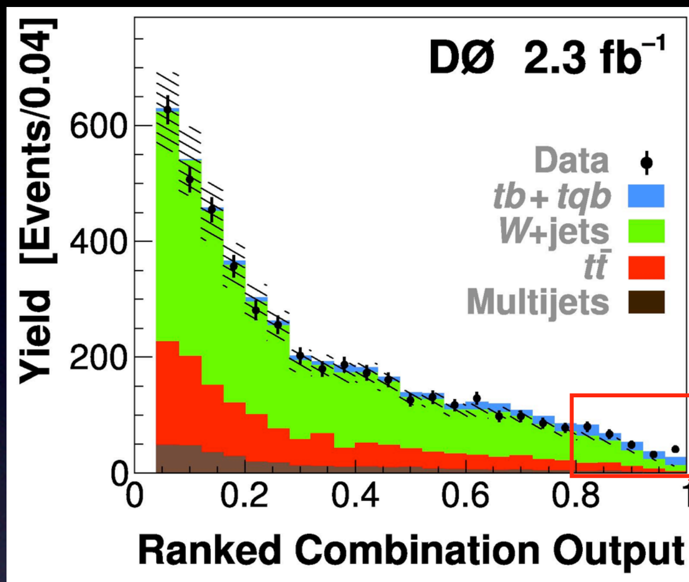
$\sigma = 2.3^{+0.6}_{-0.5}$ pb

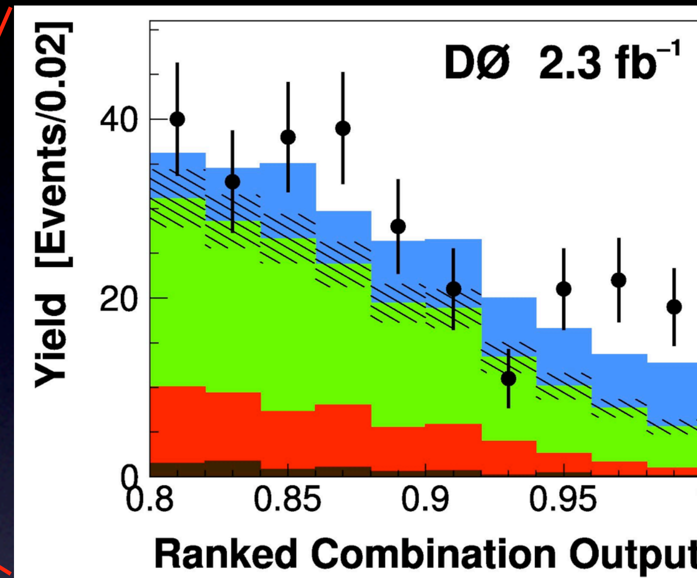
$5.0\sigma$ significance (obs) [$5.9\sigma$ exp]

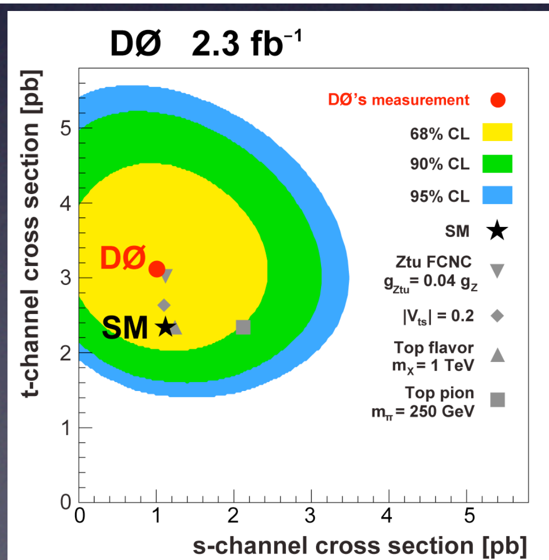
$|V_{tb}| > 0.71$ @ 95% C.L.

# Single Top at DØ

- Outputs from BDT, ME, and NN are input to final NN:




$m_t = 170$ GeV

$$\sigma_{\text{t-channel}} = 3.14^{+0.94}_{-0.80} \text{ pb}$$

$$\sigma_{\text{s-channel}} = 1.05 \pm 0.81 \text{ pb}$$

$$\sigma_{\text{total}} = 3.94 \pm 0.88 \text{ pb}$$

$5.0\sigma$ significance (obs) [$4.5\sigma$ exp]

$$|V_{tb}| > 0.78 \text{ @ } 95\% \text{ C.L.}$$

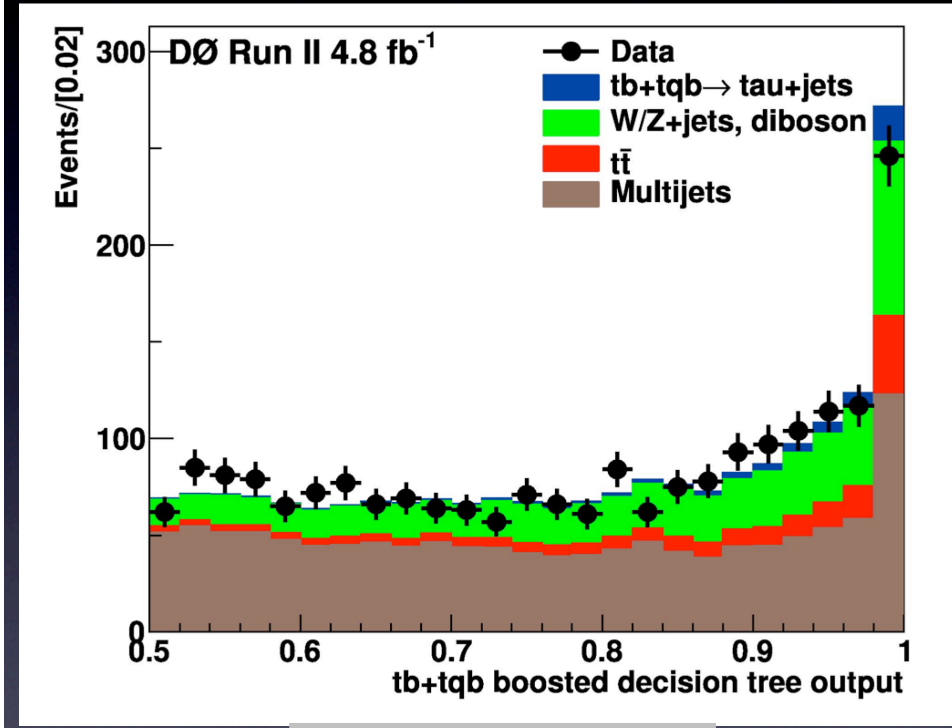
# Single Top Using τ+Jets

- τ leptons that decay hadronically appear as narrow jets with low track multiplicity
- Three distinct signatures:

1. Single track with EM subcluster
2. Single track w/o EM subcluster
3. Two or three tracks

- Identified with kinematic selection and NN specific to each signature

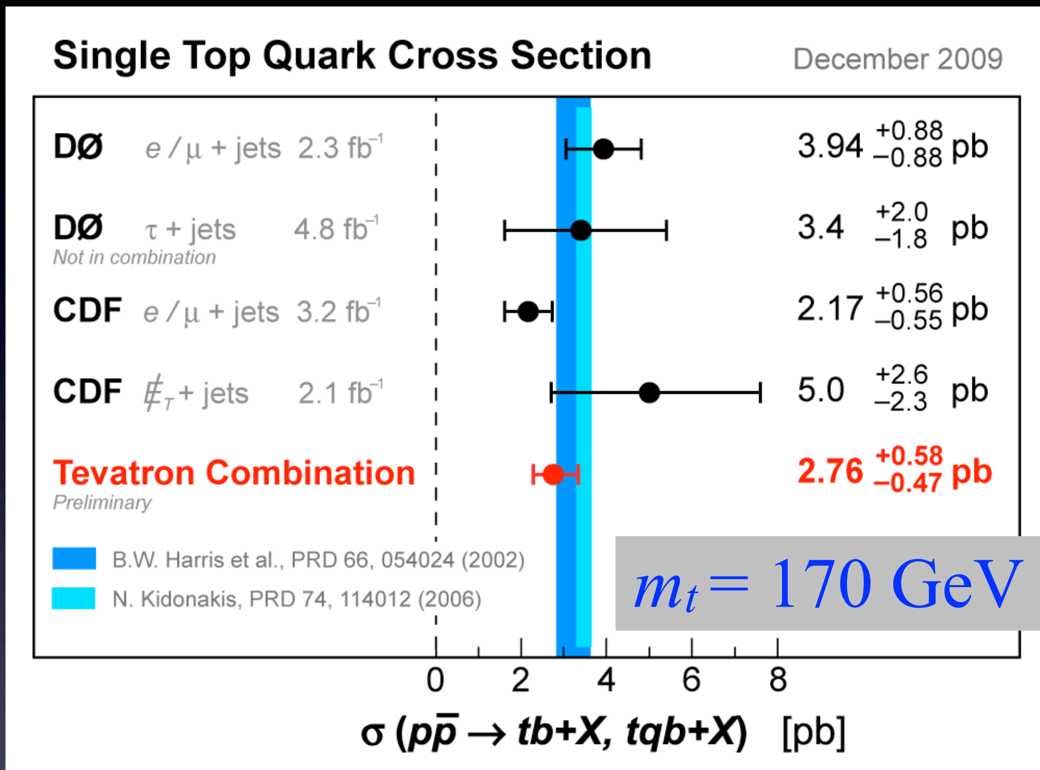
- Result of search in the τ+jets channel:

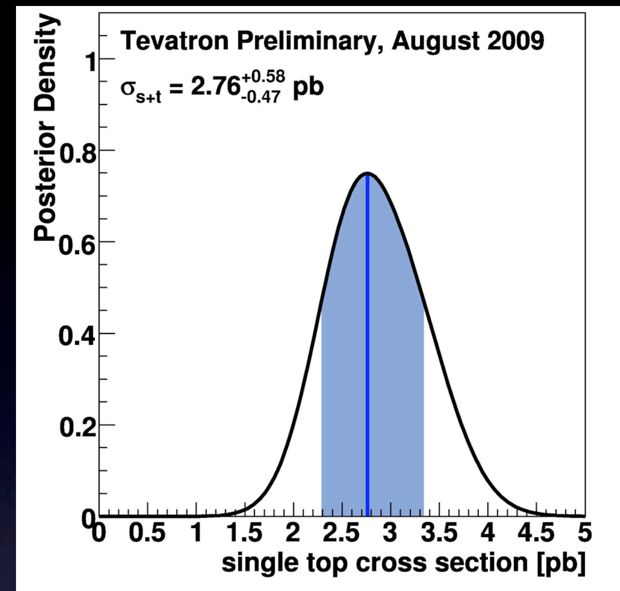


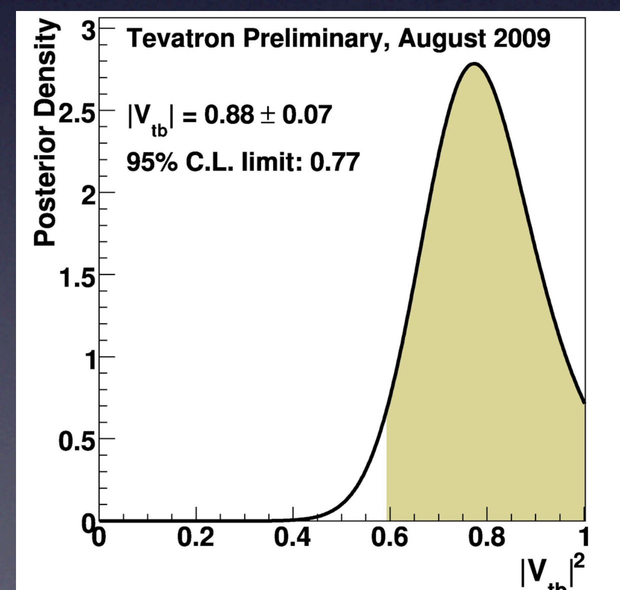

$m_t = 170$ GeV

$$\sigma = 3.4^{+2.0}_{-1.8} \text{ pb (stat. + syst.)}$$

# Combined Single Top Cross Section



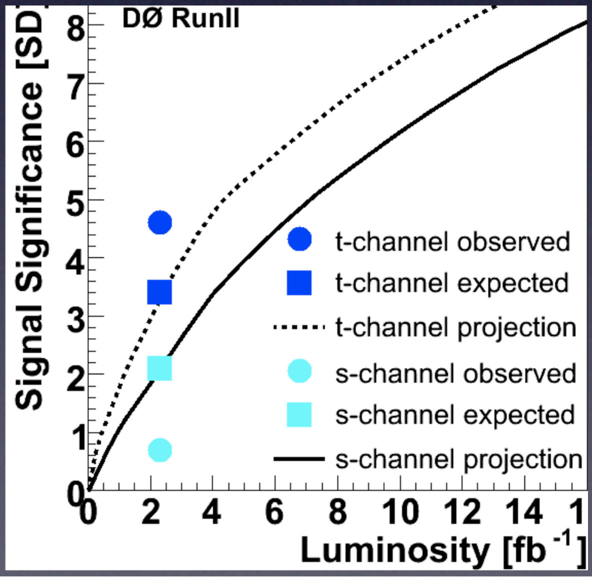




$$\sigma = 2.76^{+0.58}_{-0.47} \text{ (stat.+syst.) pb}$$
$$|V_{tb}| > 0.77 \text{ @ } 95\% \text{ C.L.}$$

# Prospects for the Future

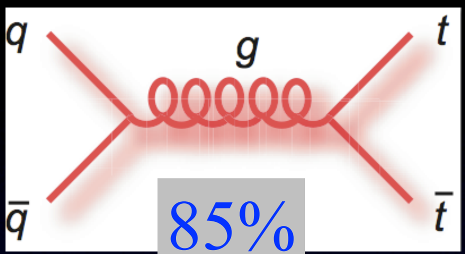
- Single top production now definitively observed
  - at rate consistent with SM expectation
- Attention now turns to improving precision and checking the SM in detail
  - measuring the s-channel cross section is critical
  - due to the $p\bar{p}$ initial state the Tevatron has an advantage over the LHC for that measurement

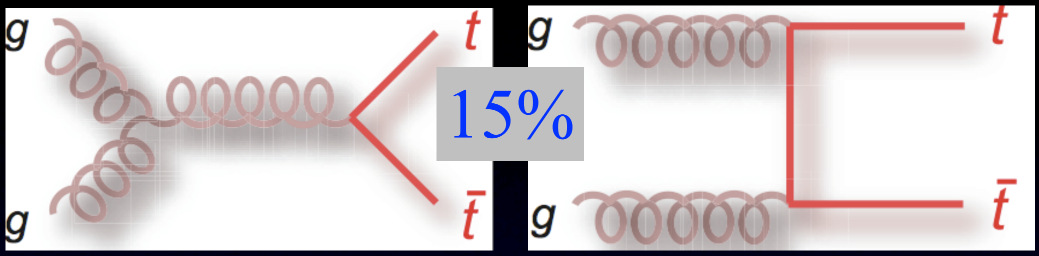



LHC will require at least 10 fb$^{-1}$ at 14 TeV for 3σ significance

# Top Quarks, Two at a Time

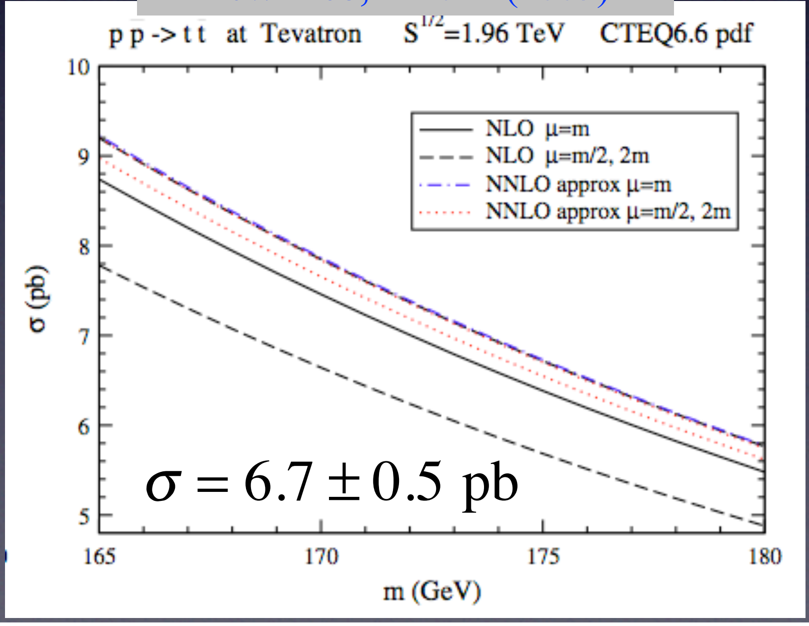
- Production at the Tevatron:




- Rate predicted in QCD at approximate NNLO:

N. Kidonakis and R. Vogt, Phys. Rev. D **68,** 114014 (2003)




$\sigma = 6.7 \pm 0.5$ pb

S. Moch and P. Uwer, Phys. Rev D **78**, 034003 (2008): $\sigma = 7.1^{+0.3}_{-0.4}$ pb

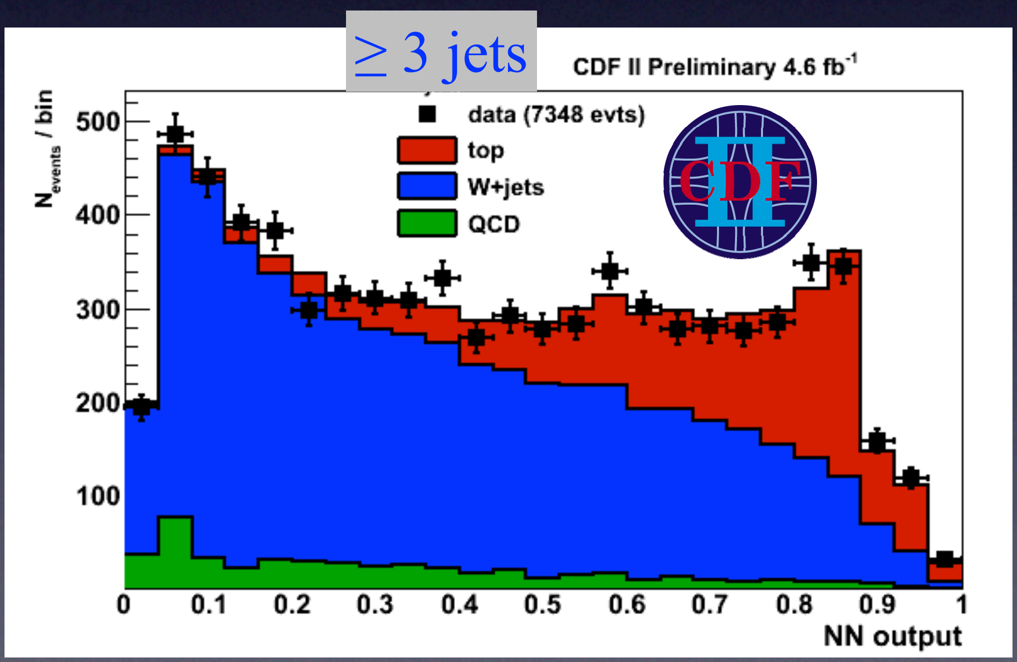
M. Cacciari *et al.*, JHEP 0809:127 (2008): $\sigma = 6.7 \pm 0.6$ pb

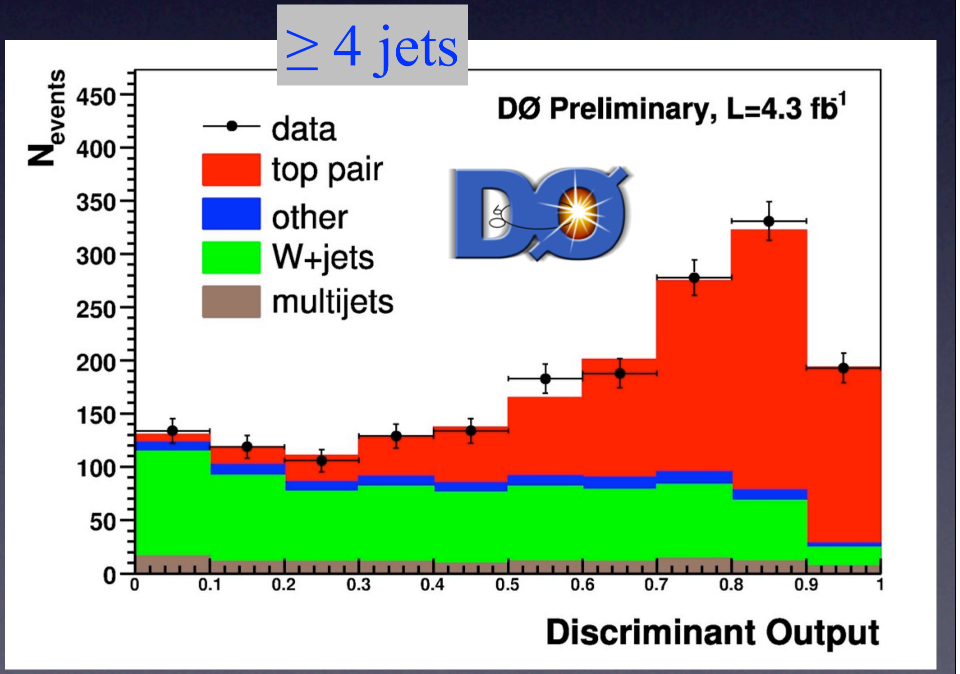
V. Ahrens *et al.*, arXiv: 1003.5827 (2010): $\sigma = 6.3^{+0.4}_{-0.3}$ pb

All numbers are for $m_t$ = 175 GeV

# Lepton + Jets Measurements

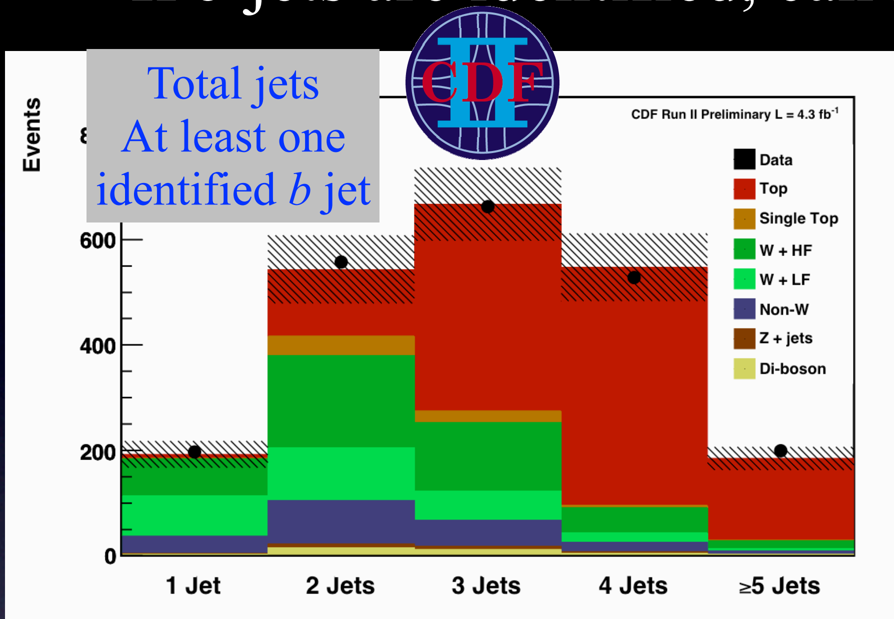
- The semileptonic decay mode offers the best combination of large $t\bar{t}$ branching fraction and low backgrounds
- Precise measurements of $\sigma\left(p\bar{p} \rightarrow t\bar{t} + X\right)$ can be made with or without requiring identified $b$ jets
  - multivariate discriminant used when $b$ lifetime information is ignored

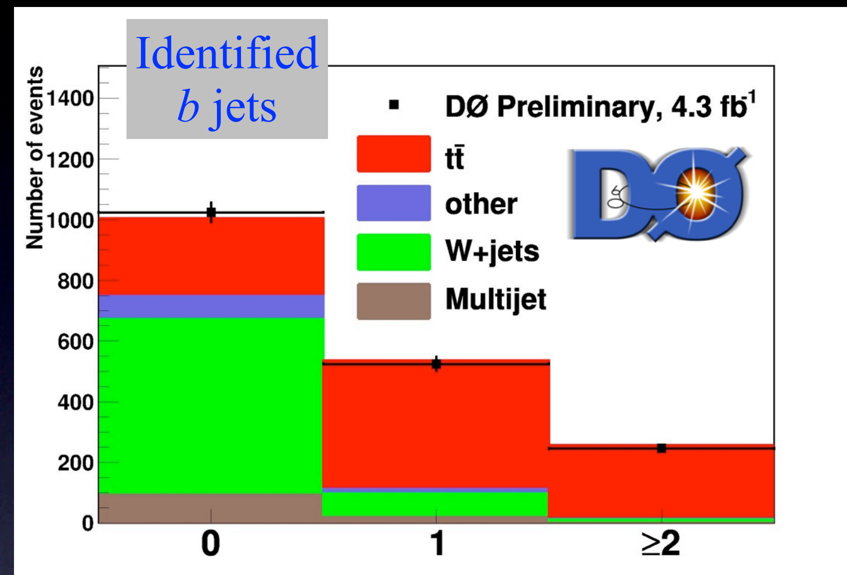


# Lepton + Jets Measurements

- If $b$ jets are identified, can look at jet multiplicity distribution




$m_t = 172.5$ GeV

Requiring an identified $b$ jet:

$$\sigma = 7.32 \pm 0.36 \pm 0.59 \pm 0.14 \text{ pb}$$

Kinematics only:

$$\sigma = 7.82 \pm 0.38 \pm 0.37 \pm 0.15 \text{ pb}$$

Requiring identified $b$ jet:

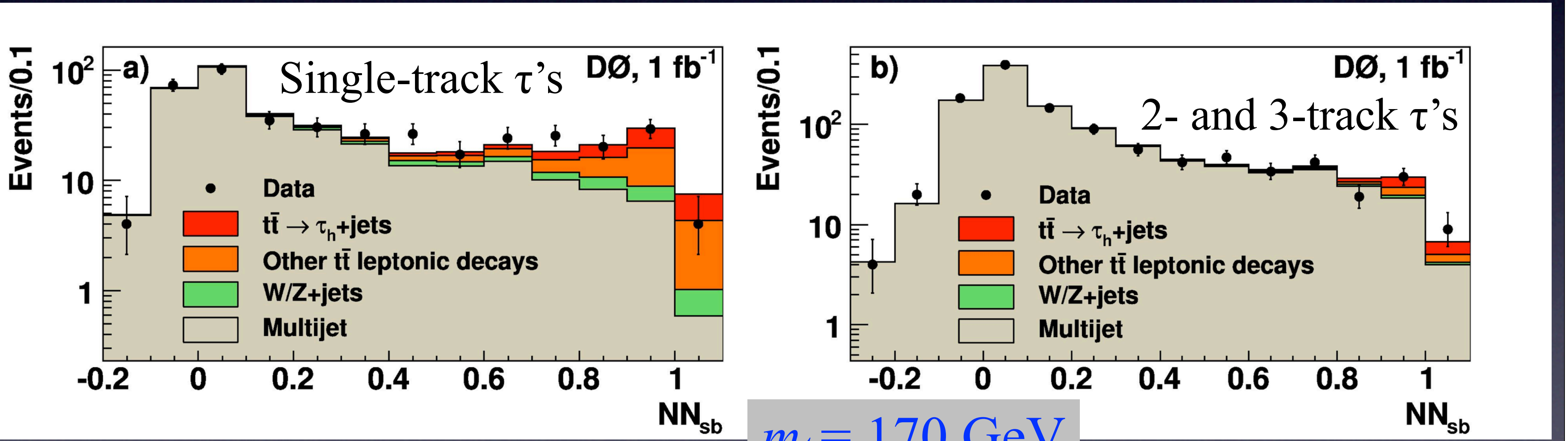
$$\sigma = 7.93^{+1.04}_{-0.91} \text{ (stat.+syst.+lumi) pb}$$

Kinematics only:

$$\sigma = 7.70^{+0.79}_{-0.70} \text{ (stat.+syst.+lumi) pb}$$

# τ+Jets Measurement

- Provides check that top quark has expected branching fractions
- Tools for identifying hadronic τ decays are similar to those in single top analysis
  - largest background is QCD multijet production where a jet appears to be a τ

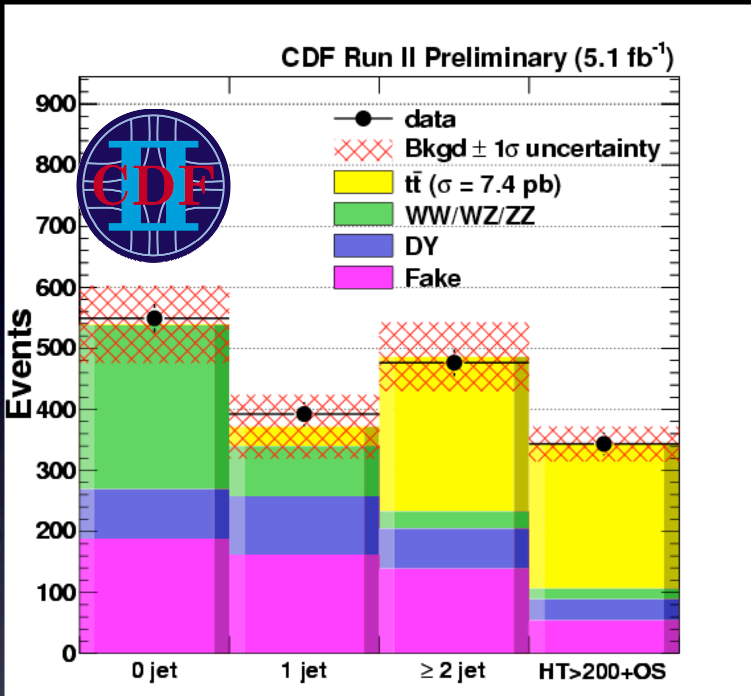


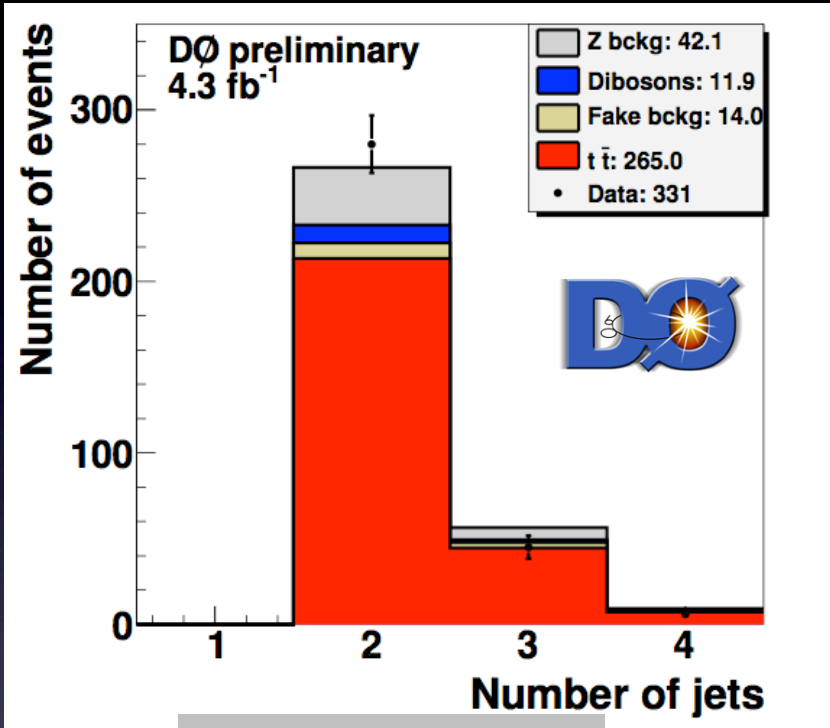

$m_t = 170$ GeV

$$\sigma = 6.9 \pm 1.2\ (\text{stat.})^{+0.8}_{-0.7}(\text{syst.}) \pm 0.4\ (\text{lumi.})\ \text{pb}$$

# Dilepton Measurements

- Dilepton channel has only ~5% $t\bar{t}$ BR, but very low backgrounds




With $b$ ID: $m_t = 172.5$ GeV

$$\sigma = 7.25 \underset{\text{stat.}}{\pm 0.66} \underset{\text{syst.}}{\pm 0.47} \underset{\text{lumi.}}{\pm 0.44} \text{ pb}$$

Kinematics only:

$$\sigma = 7.40 \pm 0.58 \pm 0.63 \pm 0.45 \text{ pb}$$

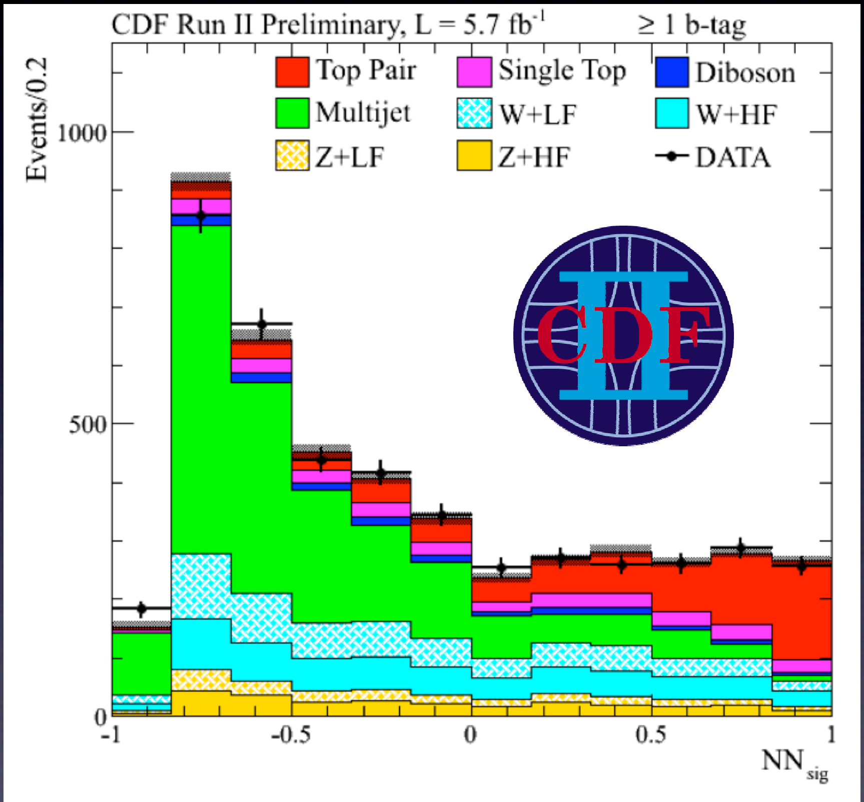
$m_t = 175$ GeV

Kinematics only:

$$\sigma = 8.23 \underset{\text{stat.}}{{}^{+0.52}_{-0.51}} \underset{\text{syst.}}{{}^{+0.85}_{-0.80}} \underset{\text{lumi.}}{{}^{+0.65}_{-0.57}} \text{ pb}$$

# Missing $E_T$ + Jets Measurement

- Unique measurement using events *without* identified leptons
  - this signature is a key background for Higgs and beyond SM physics searches
- Selection requires 2 or 3 jets, with at least one *b*-tagged
- Events then passed through two NN's
  - the first separates QCD from other events
  - the second separates $t\bar{t}$ from W/Z events

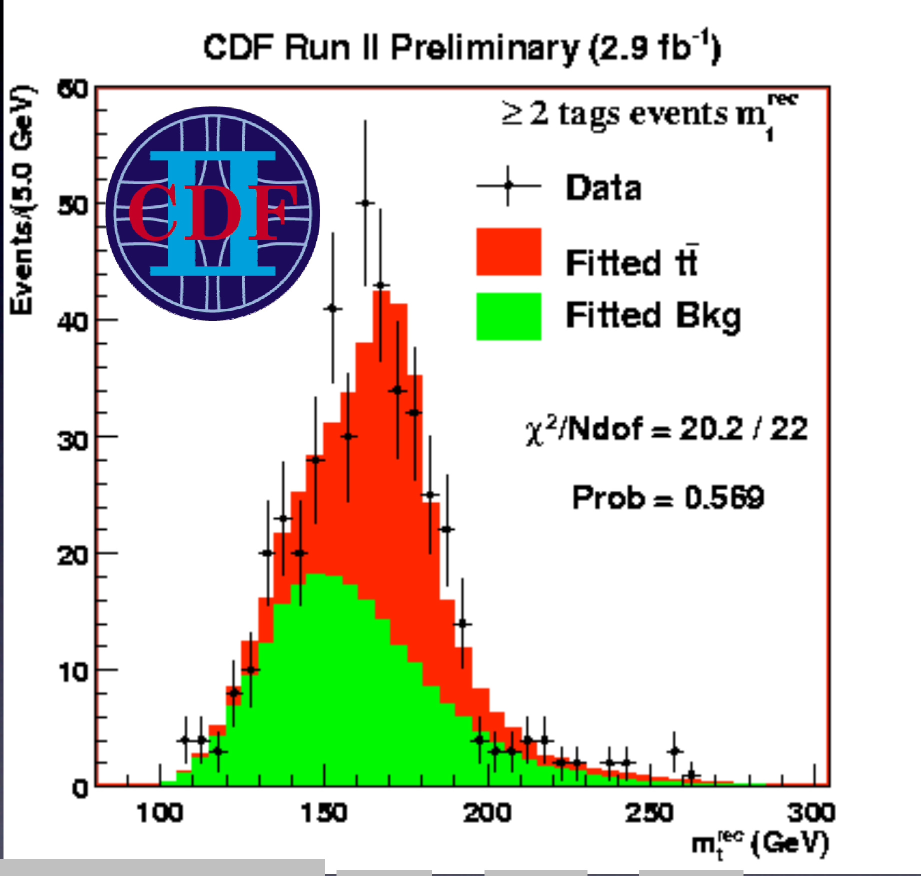


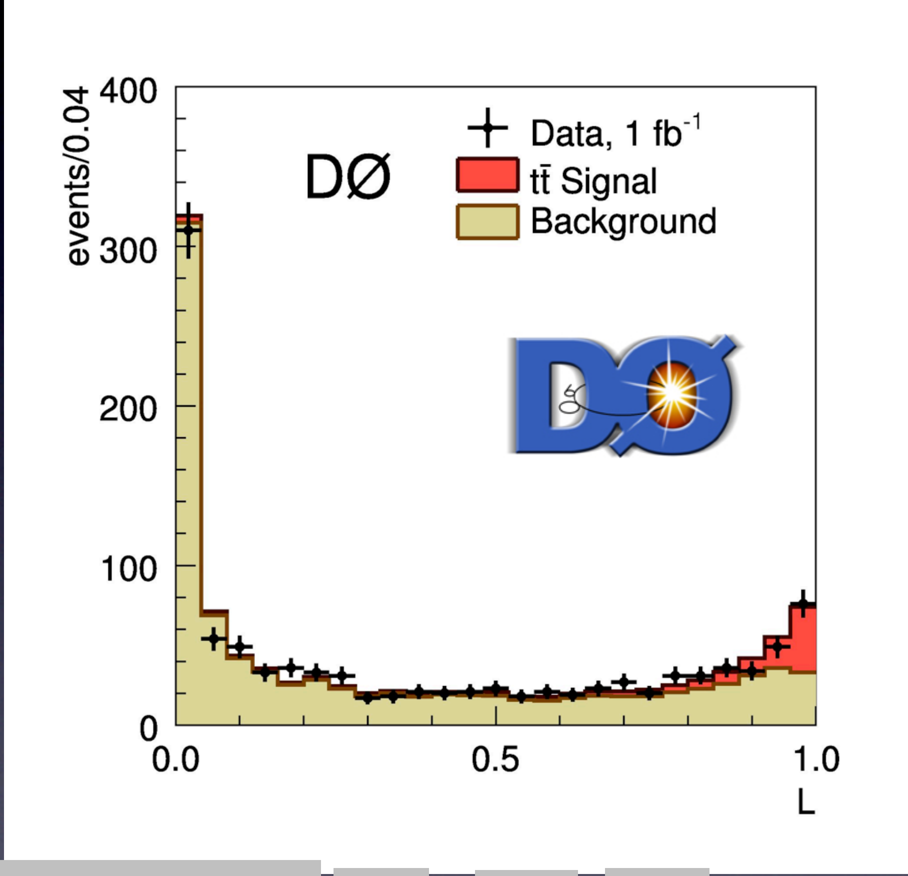

$m_t = 172.5$ GeV

$\sigma = 7.12^{+1.20}_{-1.12}$ (stat.+syst.) pb

# All-Hadronic Measurements

- Most common $t\bar{t}$ decay mode, but also most difficult to distinguish from large multijet background




$m_t = 174.8$ GeV stat. syst. lumi

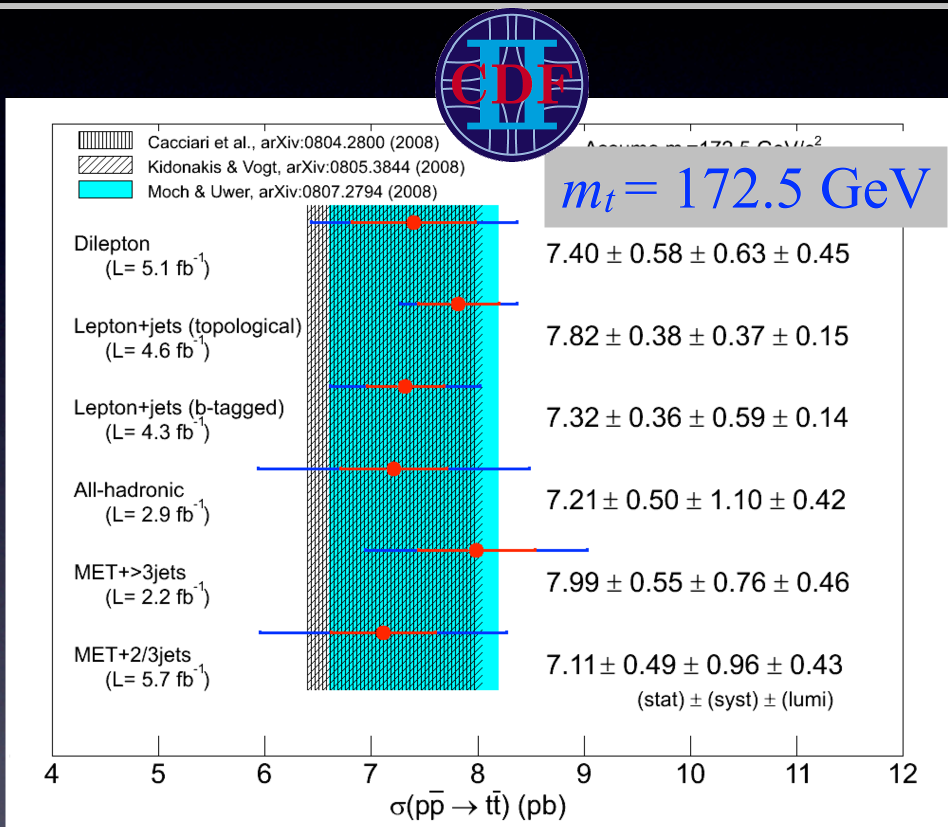
$$\sigma = 7.2 \pm 0.5 \pm 1.0 \pm 0.4 \text{ pb}$$

$m_t = 175$ GeV stat. syst. lumi

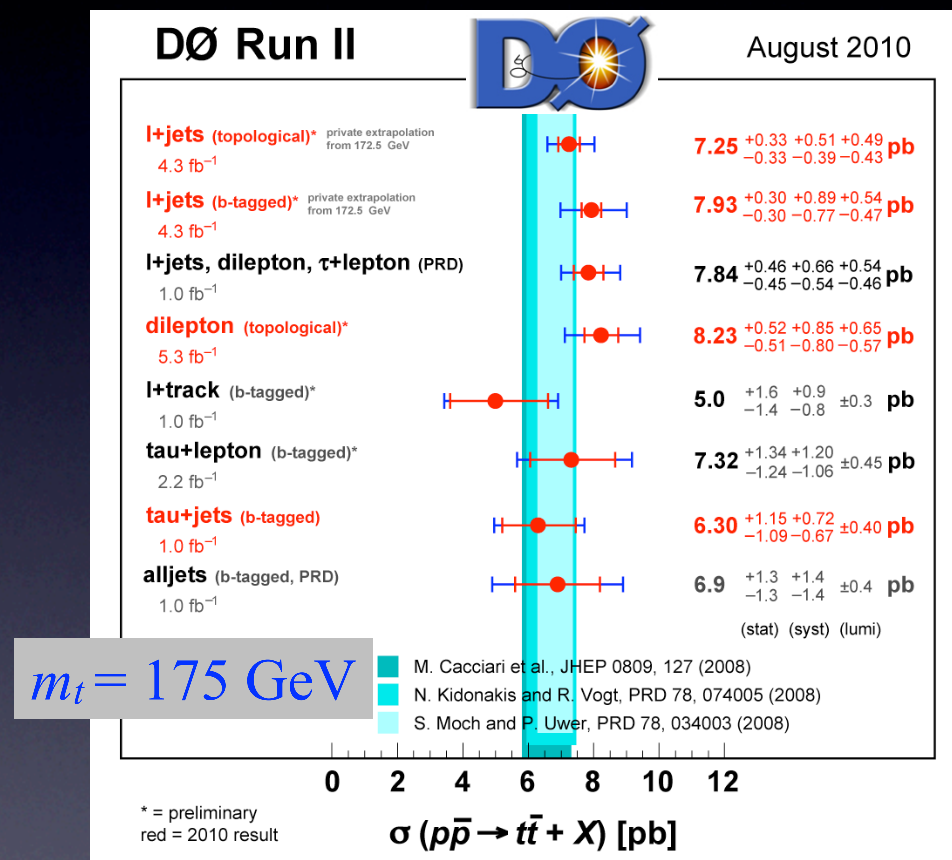
$$\sigma = 6.9 \pm 1.3 \pm 1.4 \pm 0.4 \text{ pb}$$

# Cross Section Combinations

- Caveat: recent measurements are not yet included in the combinations




$$\sigma(p\bar{p} \to t\bar{t}) = 7.50 \pm \underbrace{0.31}_{\text{stat.}} \pm \underbrace{0.34}_{\text{syst.}} \pm \underbrace{0.15}_{\text{lum.}} \text{ pb}$$

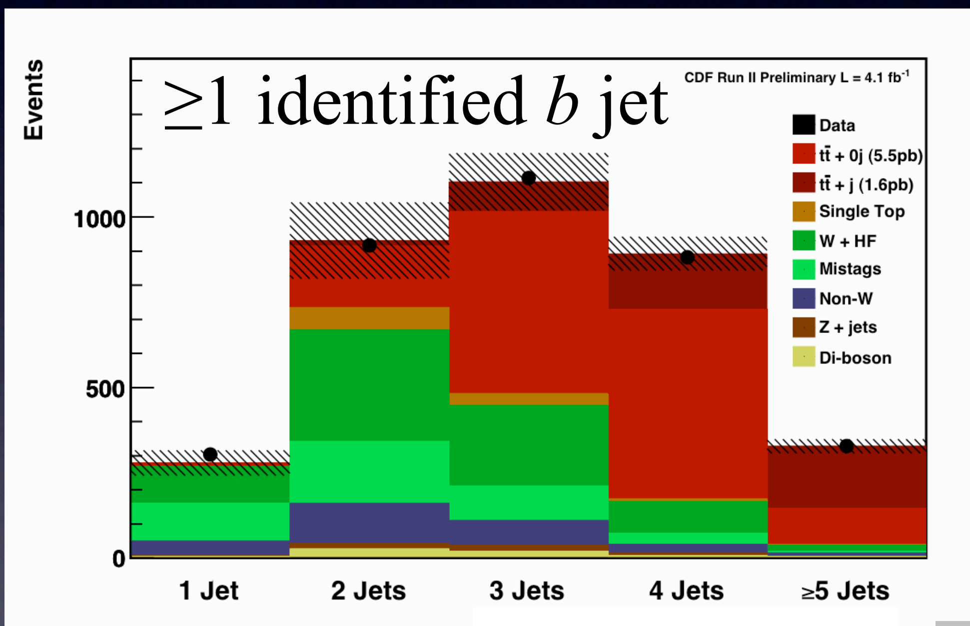



$$\sigma(p\bar{p} \to t\bar{t}) = 7.8 \pm \underbrace{0.5}_{\text{stat.}} \pm \underbrace{0.6}_{\text{syst.}} \pm \underbrace{0.5}_{\text{lum.}} \text{ pb}$$

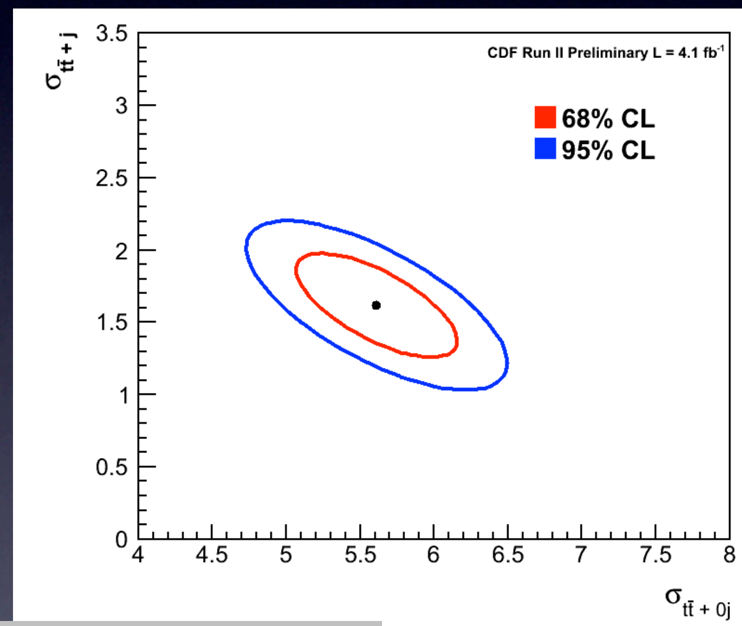
# $t\bar{t}$ + Jet Cross Section

- First measurement of production rate of $t\bar{t}$ in association with jets ($\ell$ + jets channel)
  - Test of perturbative QCD at NLO

QCD NLO prediction: $\sigma\left(p\bar{p} \to t\bar{t} + j\right) = 1.79^{+0.16}_{-0,31}$ pb




Jet multiplicity




$m_t$ = 172.5 GeV

$$\sigma\left(p\bar{p} \to t\bar{t} + j\right) = 1.6 \pm 0.2\ (\text{stat.})\ \pm 0.5\ (\text{syst.})\ \text{pb}$$

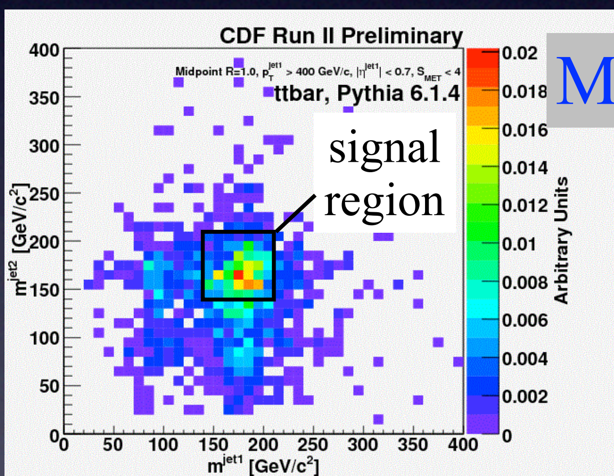
# Search for Boosted Top Quarks

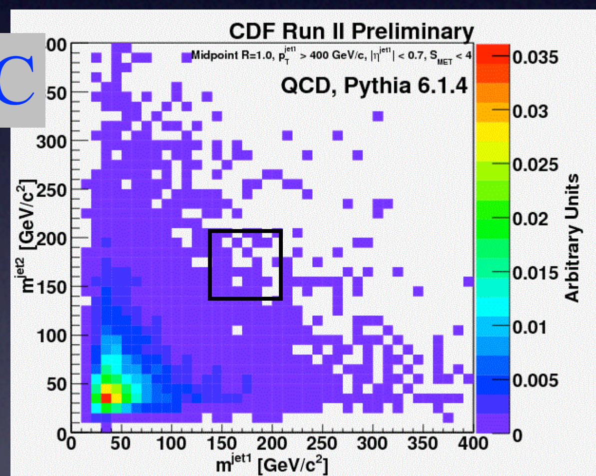
- Test of predicted top quark $p_T$ distribution
  - fraction with $p_T > 400$ GeV is expected to be $5.6 \times 10^{-4}$

N. Kidonakis and R. Vogt, Phys. Rev. D **68,** 114014 (2003)

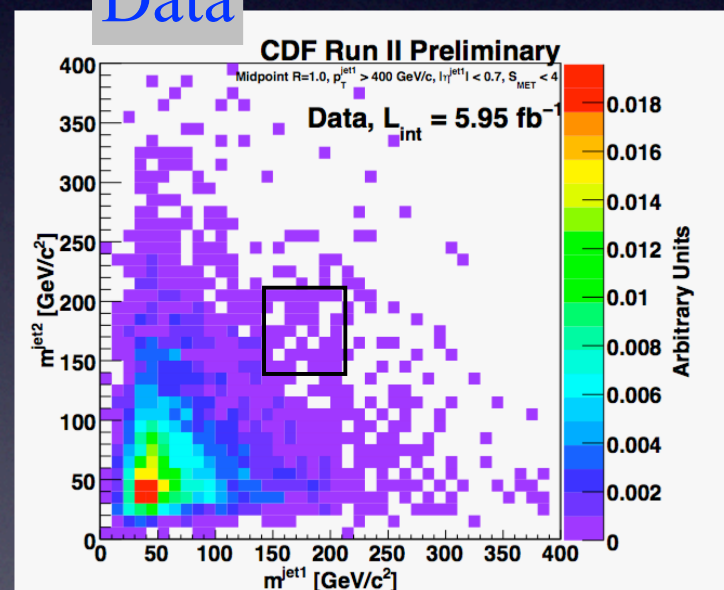
- Such highly boosted top quarks typically result in decay products merged in a single jet with large invariant mass
- All-hadronic mode:

MC




Data

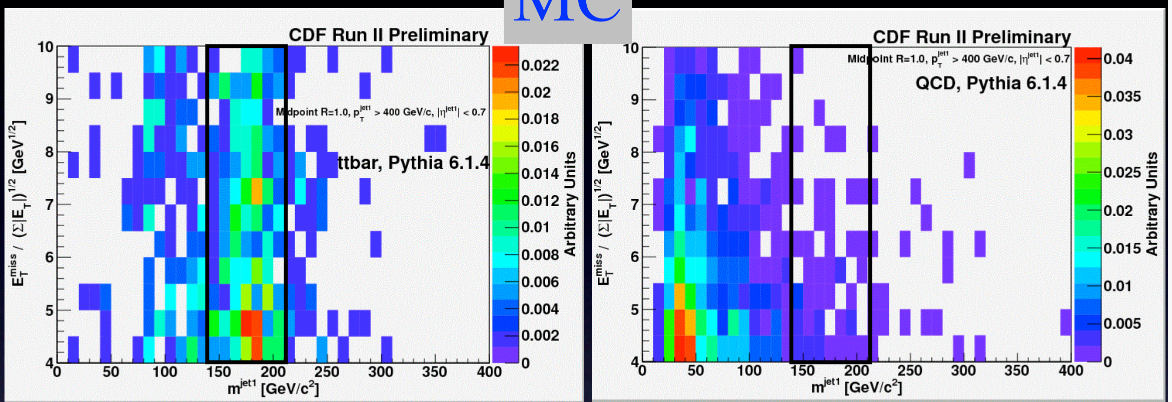



Masses of the two jets are uncorrelated

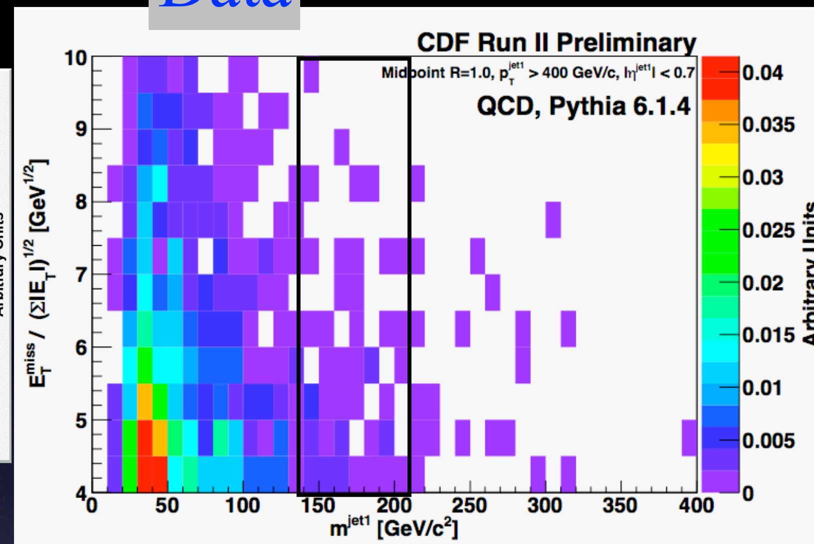
# Search for Boosted Top Quarks

- ℓ+jets channel:

MC




Data




Systematic uncertainties on yield ~40%

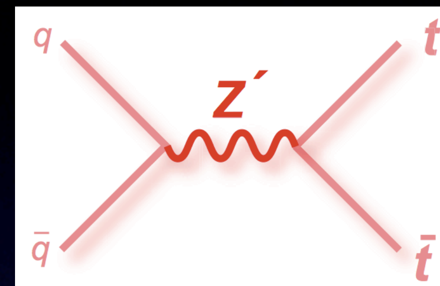
$m_t = 173$ GeV

$$\sigma(p\bar{p} \to t\bar{t} + X; p_T(t) > 400\ \text{GeV}) < 54\ \text{fb @ } 95\%\ \text{C.L.}$$

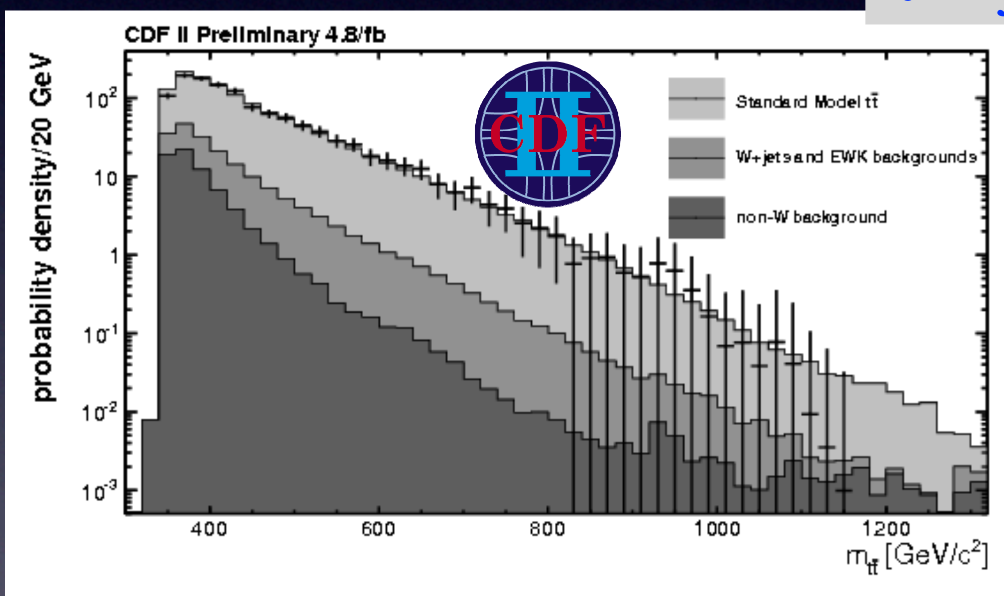
SM prediction: $4.55^{+0.50}_{-0.41}$ fb

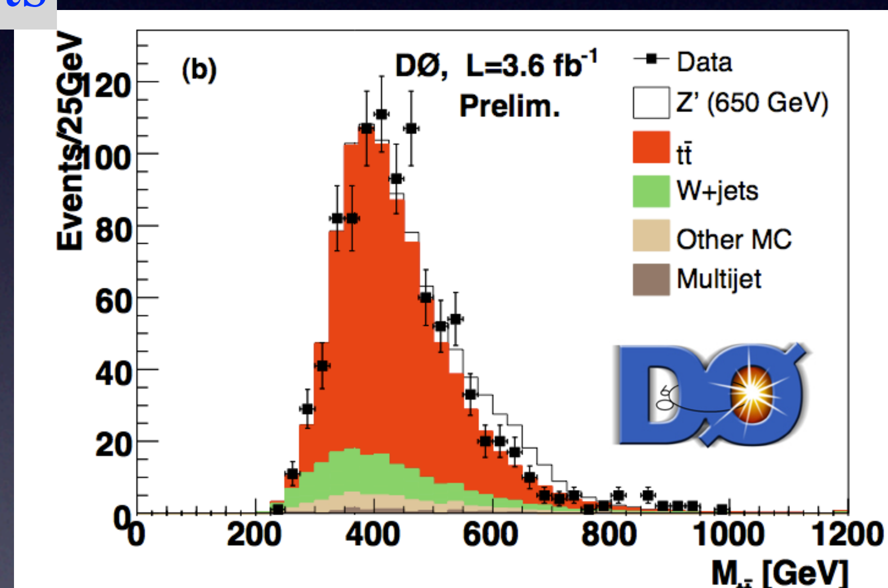
# The $M_{t\bar{t}}$ Distribution

- Non-SM distribution for $t\bar{t}$ invariant mass could indicate
  - presence of an $X \to t\bar{t}$ resonance
  - interference from non-SM process




$\ell$ + jets




$m_{Z'} > 900$ GeV @ 95% C.L.

$m_{Z'} > 820$ GeV @ 95% C.L.

# Summary

- Electroweak production of single top quarks definitively established
  - rate consistent with SM
- Top pair production cross section has been measured in many decay channels
- In addition, studies of details of the production show no discrepancies from the SM

Production measurements have provided stringent tests of the SM, and laid the groundwork for understanding the top quark's properties

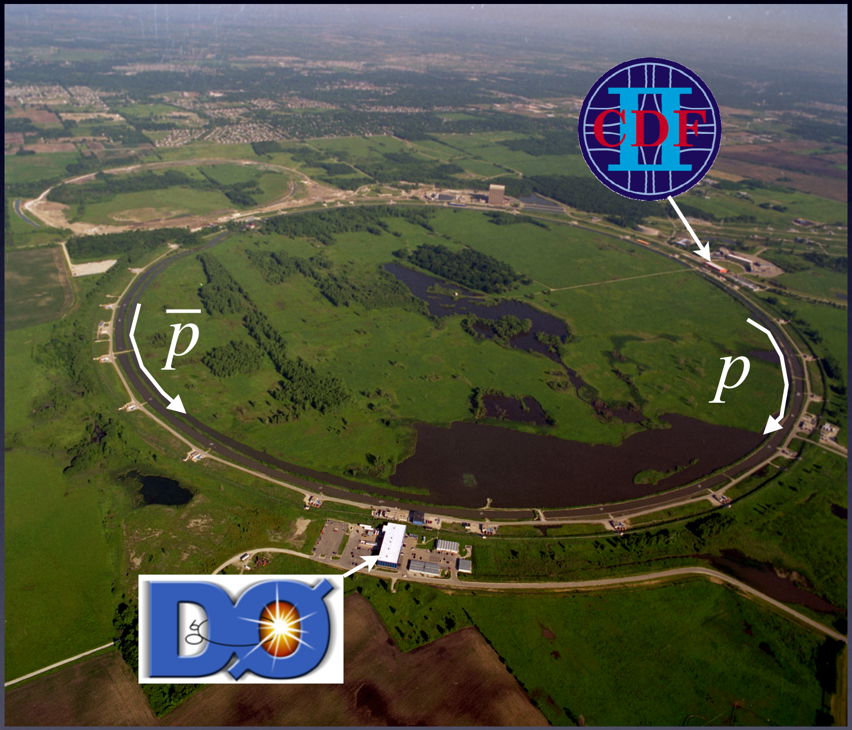
# Backup

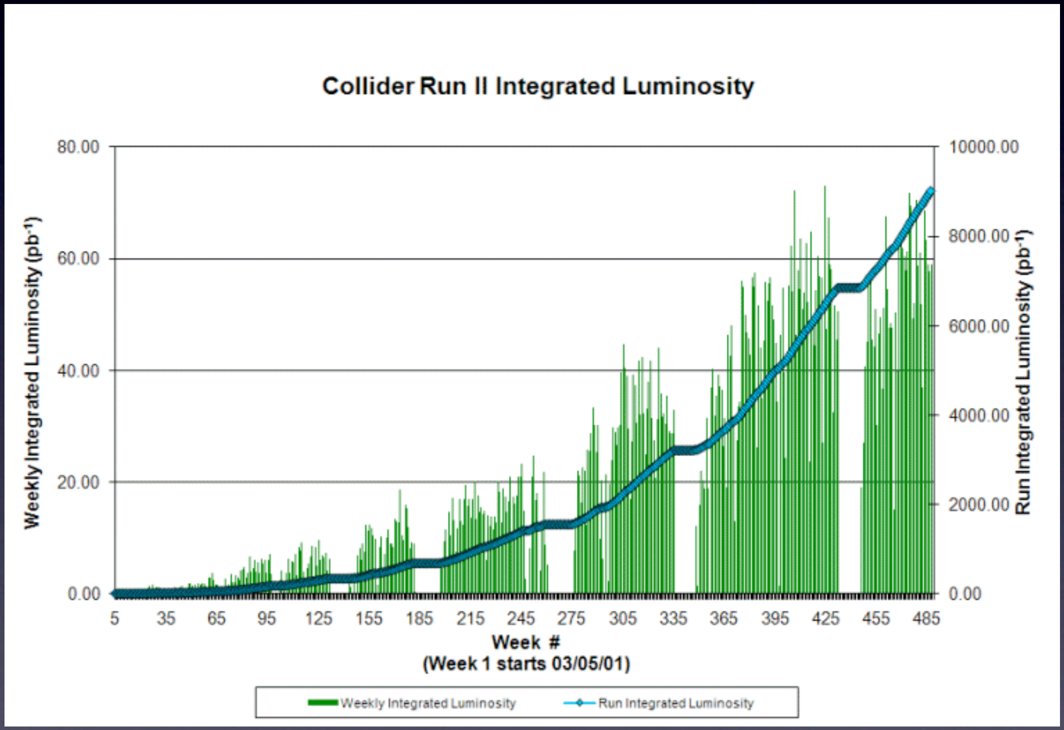
# The Top Quark in Experiment

- The world's sample of top quarks comes exclusively from the Tevatron
  - "top factory" at LHC is coming soon...
- CDF and DØ detector have similar capabilities for top quark physics
  - data samples are ~4fb$^{-1}$ per experiment ➙ ~30000 $t\bar{t}$ and 12000 single-top events produced
    - ✦ branching ratios and selection efficiencies reduce the sample available for analysis

# Fermilab Tevatron

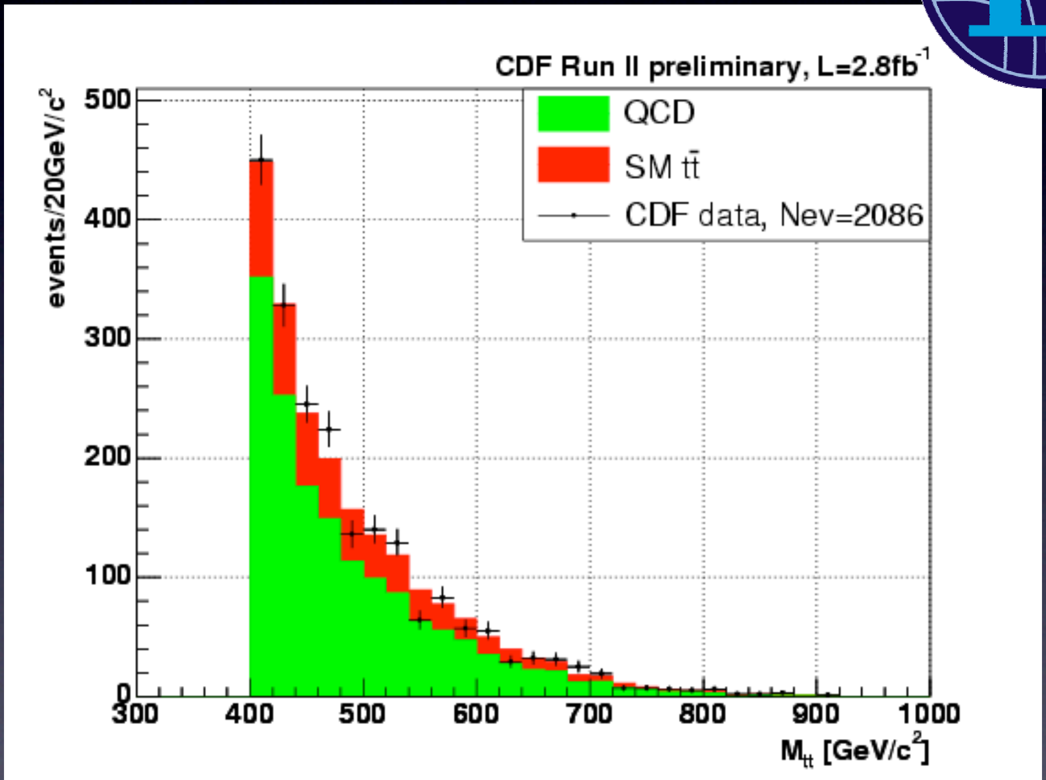
- All top production measurements so far based on data from Fermilab's Tevatron
  - though the LHC is starting to produce top quarks as well

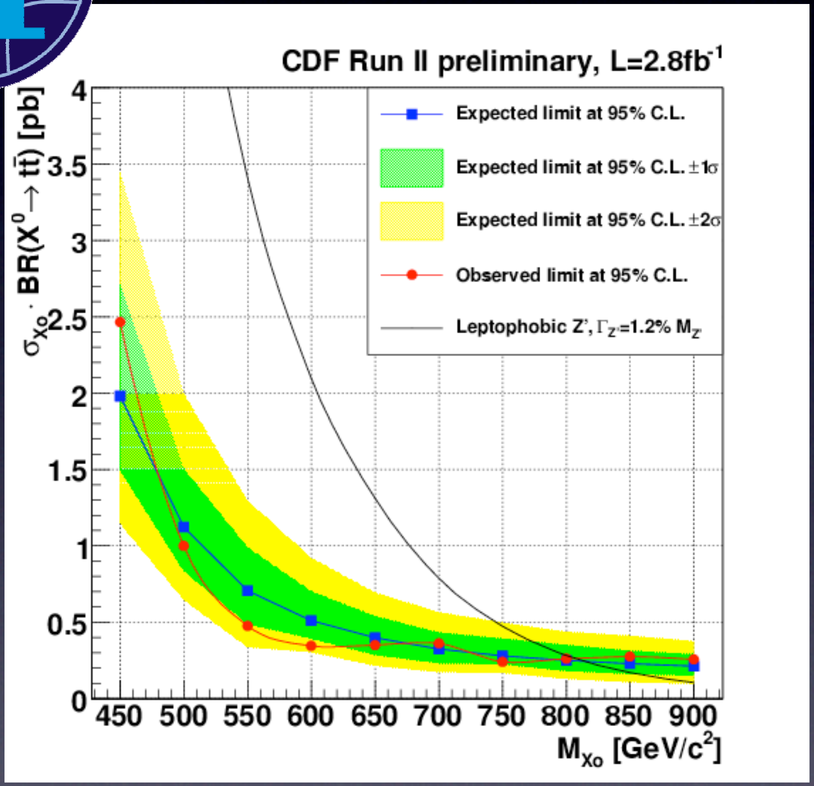


# The $M_{t\bar{t}}$ Distribution

- CDF also measures this distribution in the all-hadronic final state

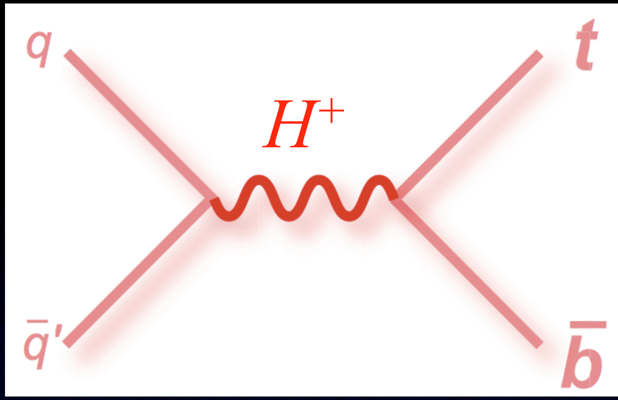


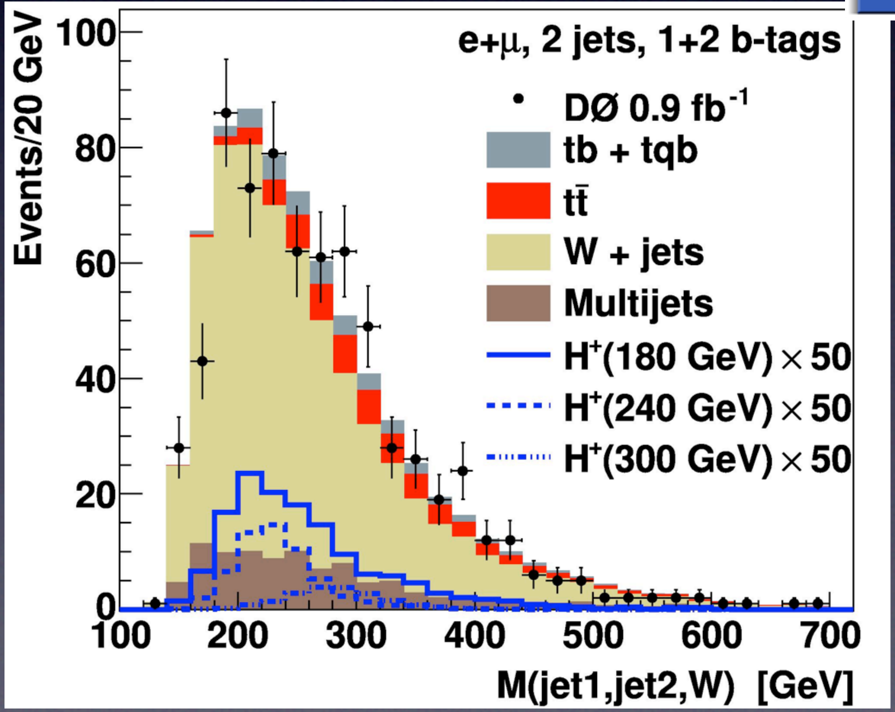



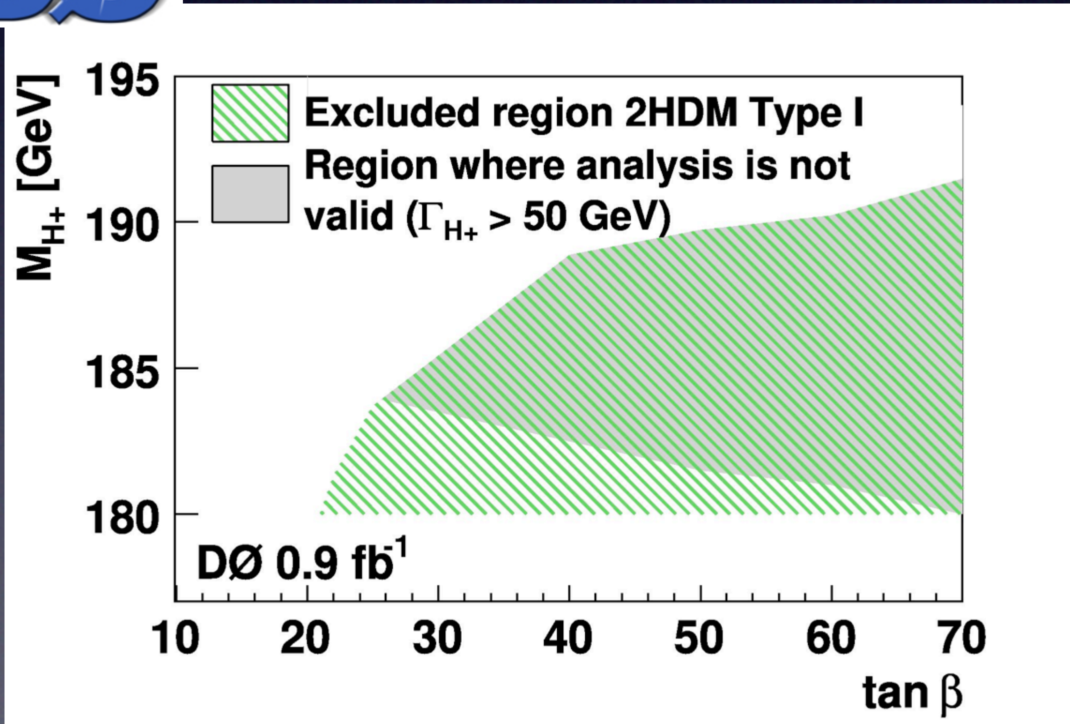

$m_{Z'} > 805$ GeV @ 95% C.L.

# Search for $H^+$ with $M_{H^+} > m_t$

- $H^+ \to t\bar{b}$ leads to the same final state as s-channel single top production
  - use single top selection to search for $H^+$
  - signals are enhanced rate and resonance in $M_{Wjj}$



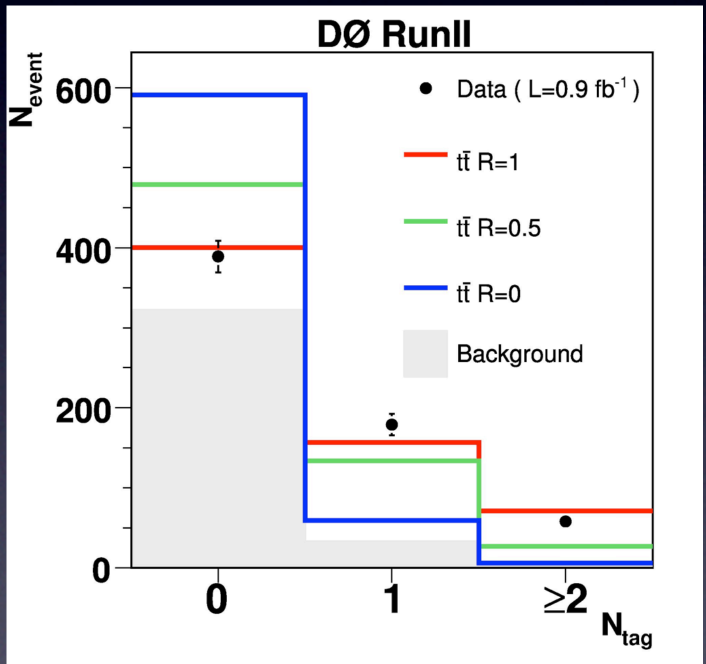



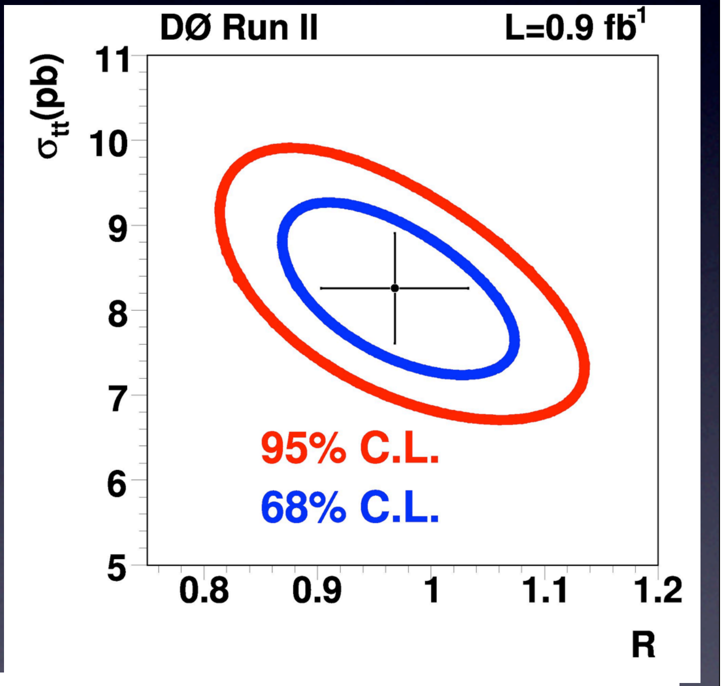



# Top Quark Branching Fractions

- Use top quark event yields with 0, 1, and 2 *b*-tagged jets to measure production cross section and $R \equiv \dfrac{B(t \to Wb)}{B(t \to Wq)}$

$$R = \frac{|V_{tb}^2|}{|V_{td}^2| + |V_{ts}^2| + |V_{tb}^2|}$$




$$R = 0.97^{+0.09}_{-0.08}$$

$$\sigma_{t\bar{t}} = 8.18^{+0.90}_{-0.84} \pm 0.50 \text{ (lumi) pb}$$

# Search for Invisible Decays

- Measure absolute rate (rather than fraction) of events with 2 $b$-tagged jets to determine $B(t \rightarrow X)$
  - sensitive to invisible top decays

$X$ is any state with different acceptance than $Wb$

Top Cross Section: Double Loose SECVTX Tag $\left(\int \mathscr{L} dt = 1.9\,\mathrm{fb}^{-1}\right)$

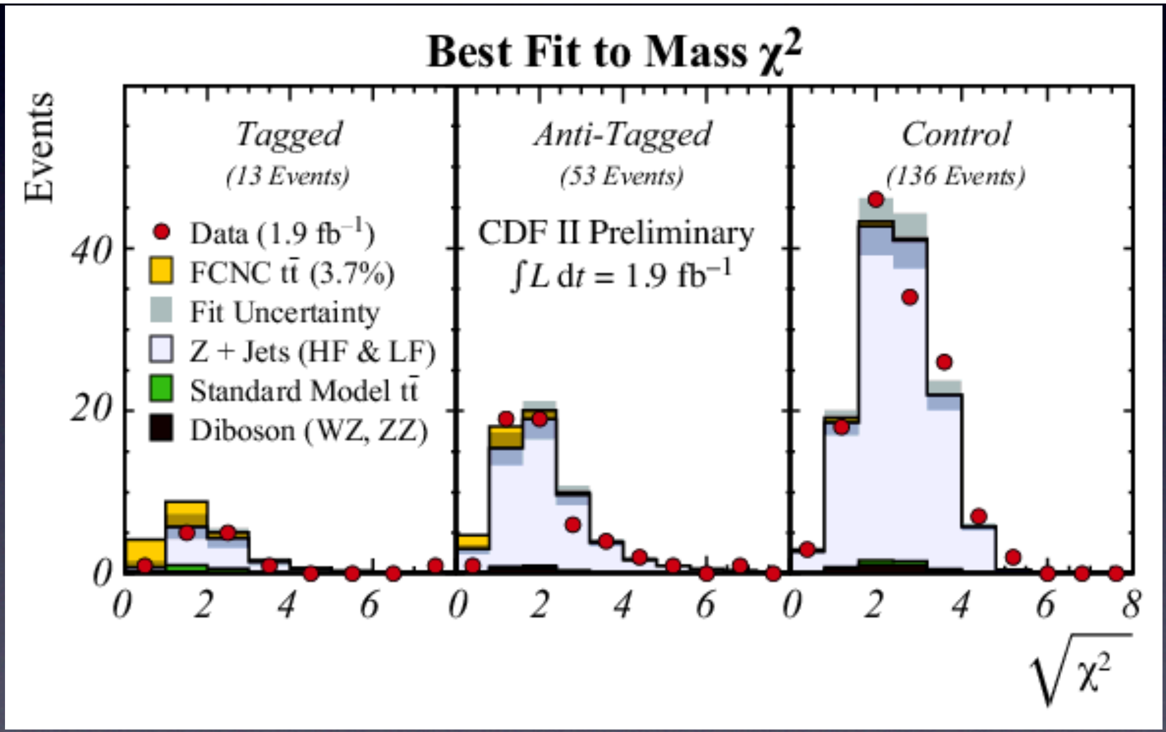
| Sample | 2 Jets | 3 Jets | 4 Jets | $\geq 5$ Jets |
|---|---|---|---|---|
| $WW$ | 0.5±0.1 | 0.5±0.1 | 0.2±0.0 | 0.1±0.0 |
| $WZ$ | 2.6±0.3 | 0.8±0.1 | 0.2±0.0 | 0.0±0.0 |
| $ZZ$ | 0.1±0.0 | 0.0±0.0 | 0.0±0.0 | 0.0±0.0 |
| Single Top ($s$) | 8.4±1.2 | 2.8±0.4 | 0.7±0.1 | 0.1±0.0 |
| Single Top ($t$) | 2.0±0.3 | 1.8±0.2 | 0.5±0.1 | 0.1±0.0 |
| $Z$+LF | 1.1±0.2 | 0.7±0.1 | 0.2±0.0 | 0.1±0.0 |
| $Wb\bar{b}$ | 33.9±13.3 | 10.6±4.3 | 2.0±0.9 | 0.5±0.2 |
| $Wc\bar{c}/Wc$ | 6.1±2.5 | 2.7±1.1 | 0.7±0.3 | 0.2±0.1 |
| Mistags | 4.3±1.0 | 2.6±0.7 | 0.7±0.2 | 0.2±0.1 |
| Non-$W$ | 2.7±1.9 | 0.8±1.5 | 0.5±1.5 | 0.2±1.5 |
| Total Background | 61.6±16.6 | 23.4±7.3 | 5.7±3.3 | 1.4±1.7 |
| SM $t\bar{t}$ (8.8pb) | 32.9±5.2 | 90.2±14.1 | 113.7±17.6 | 41.1±6.3 |
| Total Prediction | 94.5±17.4 | 113.6±15.9 | 119.4±17.9 | 42.5±6.5 |
| Observed | 107.0 | 118.0 | 115.0 | 44.0 |

$$B(t \rightarrow Zc) < 13\%$$
$$B(t \rightarrow \text{invisible}) < 9\%$$

# Flavor-Changing Neutral Currents

- SM FCNC branching fractions are are ~$10^{-14}$
  - direct searches for $t \to Zq$ are sensitive to new physics

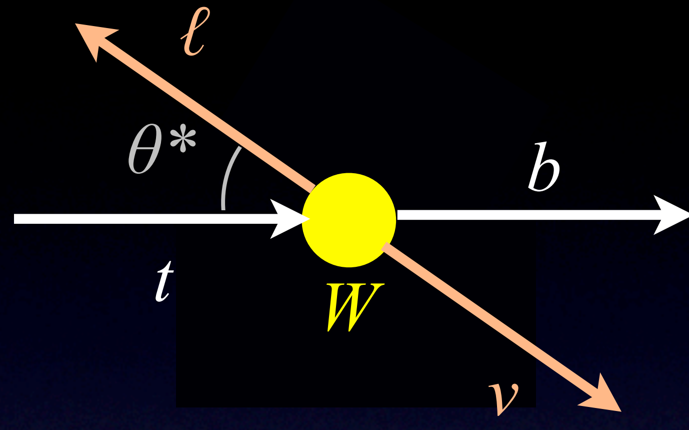
$$\chi^2 = \left(\frac{m_{W,\text{rec}} - m_{W,\text{PDG}}}{\sigma_W}\right)^2 + \left(\frac{m_{t\to Wb,\text{rec}} - m_t}{\sigma_{t\to Wb}}\right)^2 + \left(\frac{m_{t\to Zq,\text{rec}} - m_t}{\sigma_{t\to Zq}}\right)^2$$

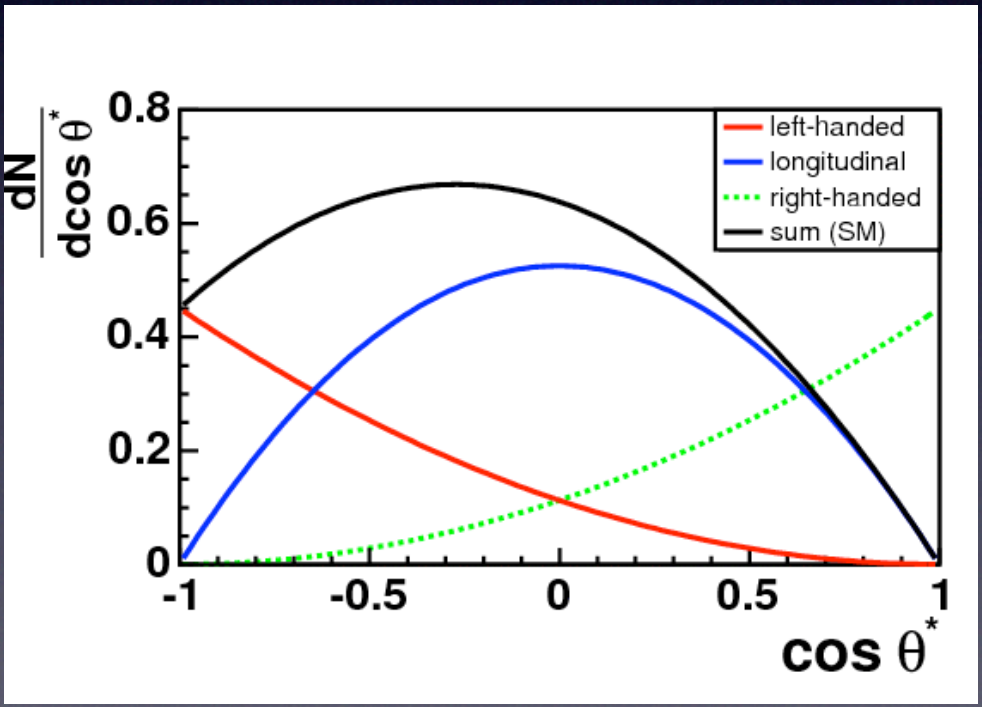



$B(t\to Zq) < 3.7\%$ @ 95% C.L.

# *W* Boson Helicity

- In the SM, 70% of *W*'s from top decay have helicity 0, 30% have helicity -1
- Direct measurements might reveal non-standard couplings



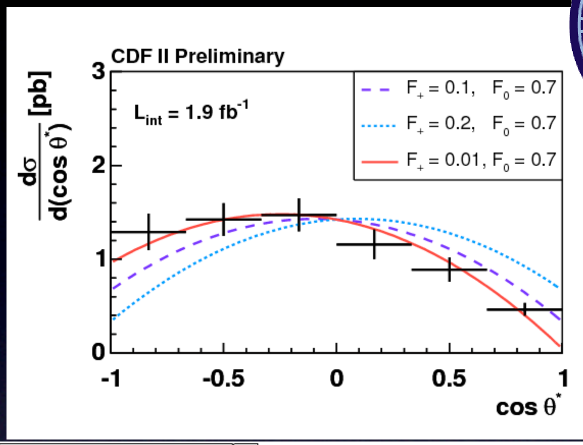

Measurement is based on direct reconstruction of cos$\theta$*

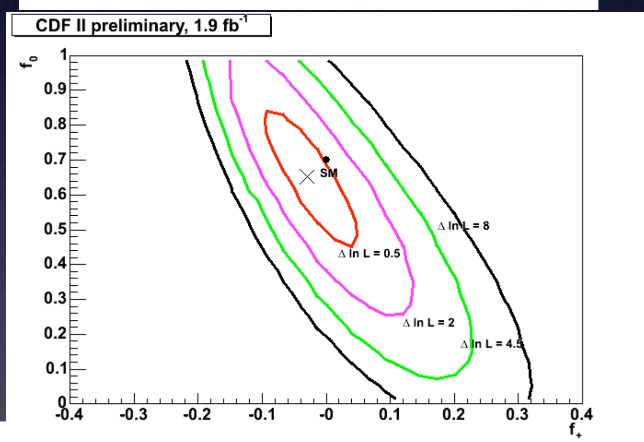
Detector and acceptance effects accounted for by:

- fit to MC templates or
- bin-by-bin unfolding

# *W* Boson Helicity

- ℓ+jets channel

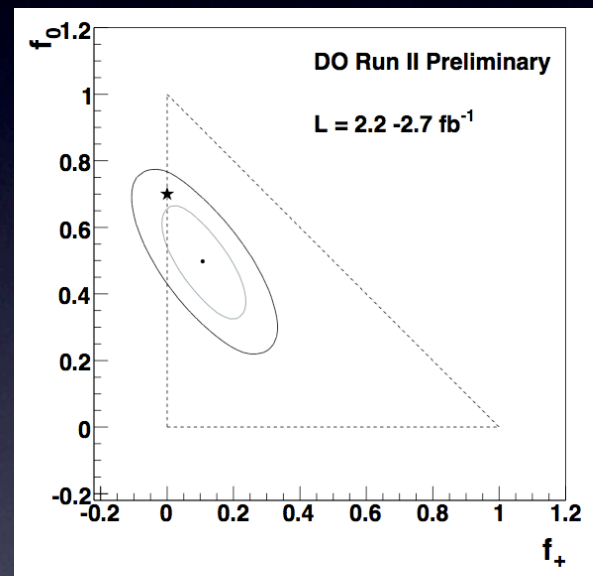



Combination:

$$f_0 = 0.66 \pm 0.16$$
$$f_+ = -0.03 \pm 0.07$$

- Template method
  - ℓ+jets and ℓℓ channels
  - use both *W*'s in each event

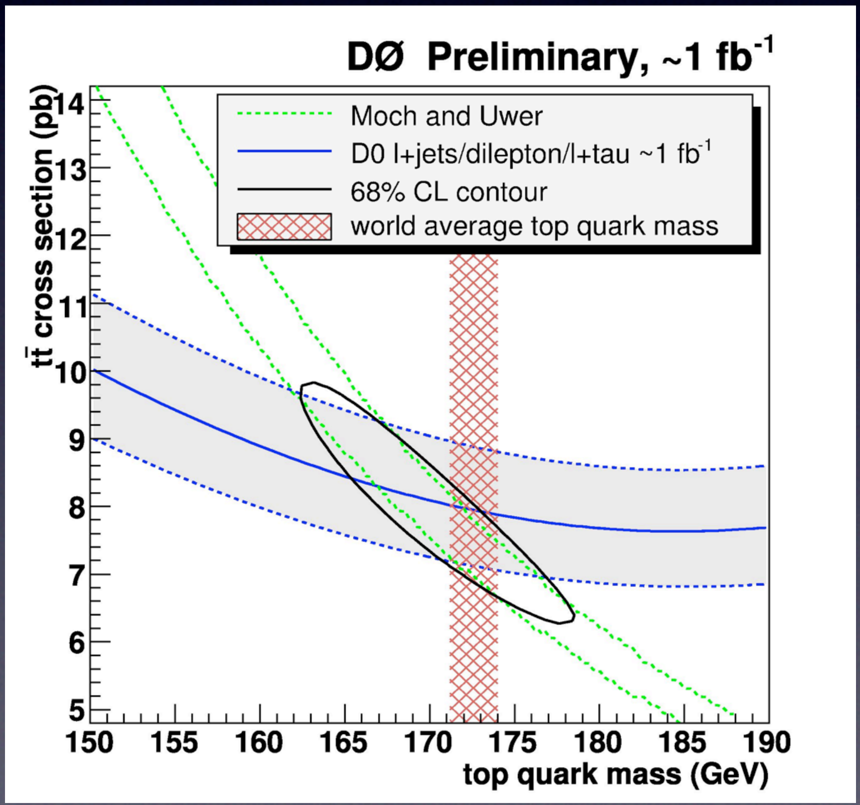



$$f_0 = 0.49 \pm 0.10 \pm 0.08$$
$$f_+ = 0.11 \pm 0.05 \pm 0.05$$

SM *p*-value: 23%

# Mass Measurement from Cross Sections

- Assuming that production is governed by SM, can compare measured to calculated cross sections to extract top mass
  - mass is measured in a well-defined renormalization scheme
  - systematics largely uncorrelated with other methods




NLO+NLL cross section:

M. Cacciari *et al.* (2008)

$$m_t = 167.8 \pm 5.7 \text{ GeV}$$

Approx NNLO cross section:

S. Moch and P. Uwer (2008)

$$m_t = 169.6 \pm 5.4 \text{ GeV}$$

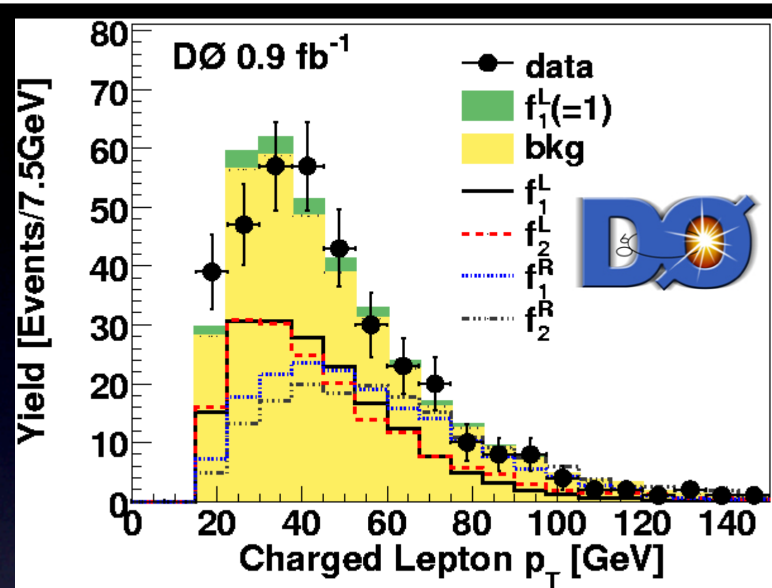
# Constraints on *Wtb* Couplings

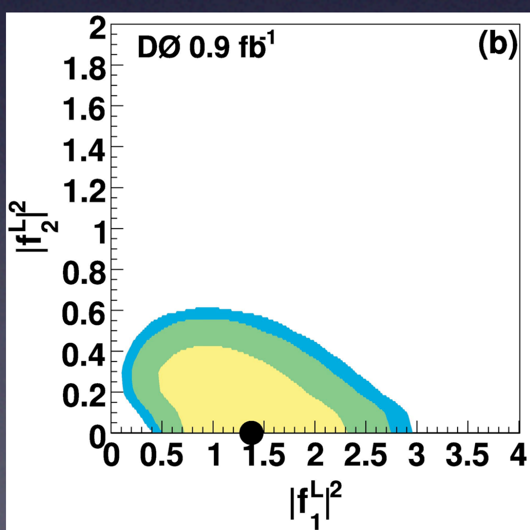
- Rate and kinematic distributions in single top events depend on the *Wtb* coupling structure

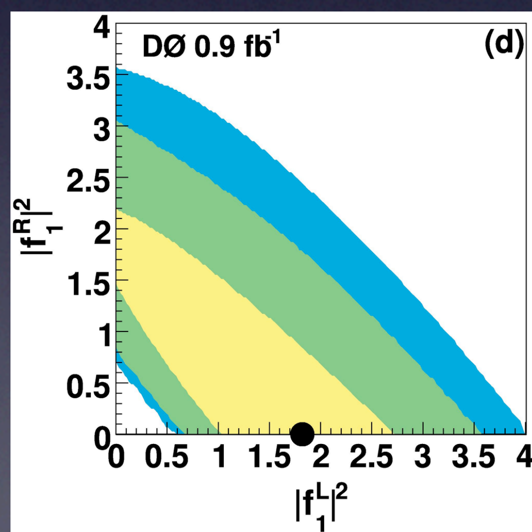
$$\mathcal{L} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b}\gamma^\mu \left(f_1^L P_L + f_1^R P_R\right) t$$

$$- \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R\right) t + h.c.$$

In SM: $f_1^L = |V_{tb}| \approx 1,\ f_1^R = f_2^L = f_2^R = 0$




| Allowed couplings | Measured values |
|---|---|
| $f_1^L, f_2^L$ | $\left\|f_1^L\right\|^2 = 1.4^{+0.6}_{-0.5},\ \left\|f_2^L\right\|^2 < 0.5$ |
| $f_1^L, f_1^R$ | $\left\|f_1^L\right\|^2 = 1.8^{+1.0}_{-1.3},\ \left\|f_1^R\right\|^2 < 2.5$ |
| $f_1^L, f_2^R$ | $\left\|f_1^L\right\|^2 = 1.4^{+0.9}_{-0.8},\ \left\|f_2^R\right\|^2 < 0.3$ |